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TRANSACTIONS.

No. 776.

FLOW OF WATER IN 48-IN. PIPES.

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PRESENTED FEBRUARY 5TH, 1896.

WITH DISCUSSION.

The experiments here described were made in 1894-95 on the Rosemary inverted siphon, a part of the Sudbury Aqueduct supplying the city of Boston with water. As the pipes had been in use sixteen years it was thought that it would be of value to determine how much their capacity had been diminished by the increased friction due to the incrustation of the interior surfaces. A series of experiments was planned in 1893, but it was not until September, 1894, that all the preparations were completed, the weirs and piezometers erected, and the experiments begun. Many delays and difficulties were encountered from the fact that much of the work had to be done inside the aqueduct, which was in regular service, so that the flow could be stopped only for short intervals.

Description of the Siphon.—The Sudbury River Aqueduct is 17.4 miles long, and for the greater part of its length it is 7 ft. 8 ins. high and 9 ft. wide. At a distance of 11.7 miles from its head at Framingham the

water is carried across the valley of Rosemary Brook through two 48-in. cast-iron mains, 1 800 ft. long, laid side by side on a straight line in plan, and descending gradually into the valley to a grade about 48 ft. below the bottom of the aqueduct, forming an inverted siphon (see profile, Fig. 1). The changes of gradient are made with vertical curves. The ends of the pipes are furnished with gate-chambers covered with substantial masonry buildings. The pipes were laid in 1877, and were first put into service in 1878; they were of the usual hub and spigot form, cast in lengths of 12 ft. The pipes were coated with Dr. Angus Smith's coal-tar preparation. The joints were well made. Two diameters were measured at each of 37 stations; the mean diameter thus obtained was 3.998 ft., taken as 4 ft. An attempt was made to figure the diameter by filling the pipe with water which was first passed over a small standard weir. It was found impossible to arrive at as correct a result by this method as by measurements of the pipe.

Before beginning the experiments, photographs were made by flash light of the interior of the pipes showing the tuberculated surfaces. Two of these photographs are reproduced on Plate VIII, Figs. 1 and 2. It was estimated that the tubercles covered nearly one-third of the interior surfaces, the bottom being more thickly incrusted with them, while the tops and sides of the pipes were cleaner.

Scheme of Experiments.—The losses of head were measured as near the extremities of the pipe as it was wise to place the piezometers, and in two ways, first, by a set of piezometers screwed into the pipes, and second, by tube gauges placed lengthwise on the bottom of the pipes and connecting with lead pipes extending out of the open ends to gauge chambers. The former method was more elaborately carried out and was considered the principal one. The latter had been adopted by F. P. Stearns, M. Am. Soc. C. E., in his experiments at the same place, and by using it in addition it was expected that a valuable check on the results would be secured.

It was found impossible to arrange a weir measurement in the aqueduct near the siphon which would admit of a greater velocity than about 3.7 ft. per second through one pipe. It was therefore determined to measure the flow up to this velocity through each pipe in turn; then to scrape all the tubercles from one pipe and experiment again upon the pipe as cleaned; then to erect two weirs at the terminus of the

PLATE VIII.
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FITZGERALD ON FLOW OF WATER IN PIPES.

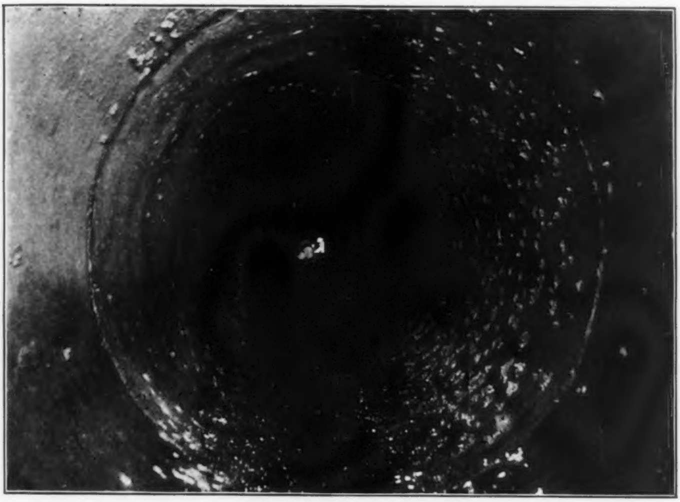


Fig. 1.

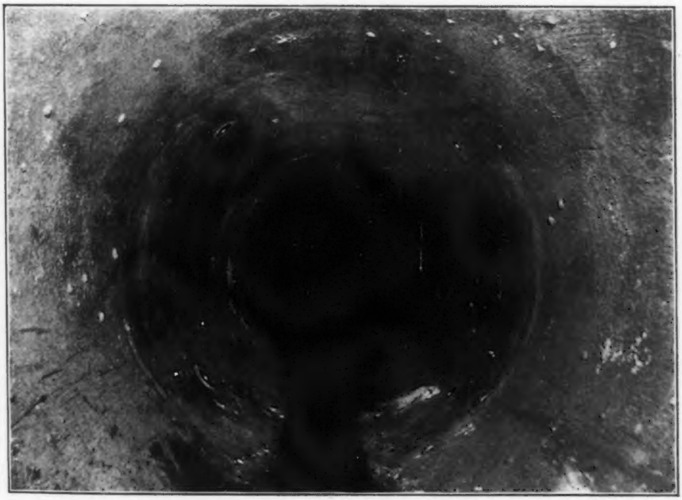


Fig. 2.

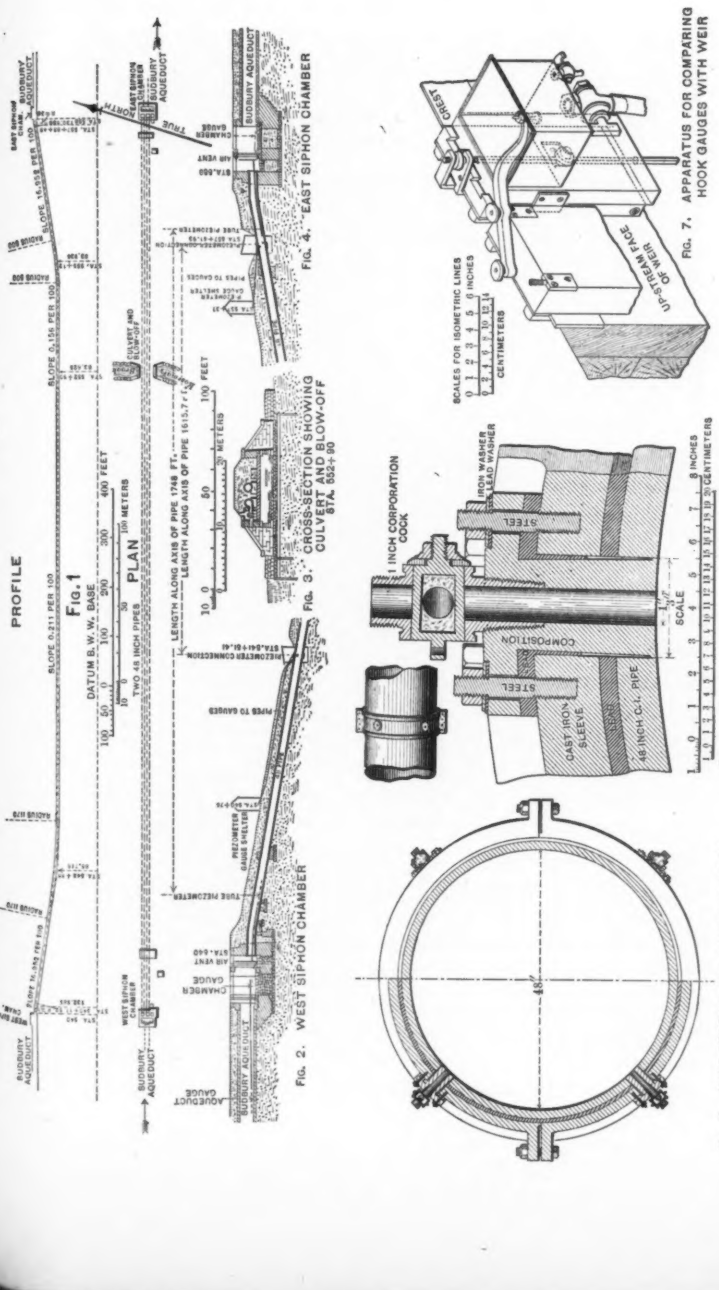


FIG. 2. WEST SIPHON CHAMBER

FIG. 3. CROSS-SECTION SHOWING CULVERT AND BLOW-OFF STA. 552+90

FIG. 4. EAST SIPHON CHAMBER

FIG. 5. HALF SECTION AND HALF-ELEVATION OF SLEEVE

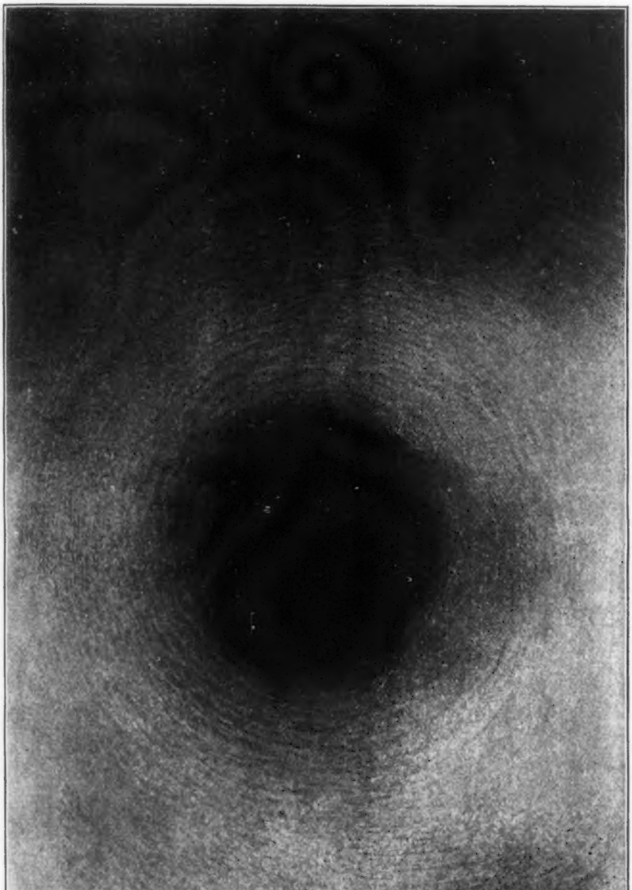
FIG. 6. SECTION THROUGH PIEZOMETER

FIG. 7. APPARATUS FOR COMPARING HOOK GAUGES WITH WEIR

aqueduct at Chestnut Hill Reservoir about 5.3 miles distant, and connect the weir measurement at the siphon with the weir measurement at the terminal chamber by means of an extended series of observations which would give a comparison between them at different rates of flow up to about 45 cu. ft. per second. The siphon weir was then to be taken out in order to secure as high a velocity as possible in one pipe, the discharge being measured by means of the weirs at the terminal chamber.

This general programme was carried out. The new weirs of course held back the water in the aqueduct, and it required a careful adjustment of the hydraulic gradient to arrange for the desired flow; but the coefficient of friction of the aqueduct was well known, as was the approximate coefficient of the pipes after the first series of experiments had been completed. Observations were begun on September 4th, 1894, upon the south pipe, tuberculated, and were continued on this pipe at various times up to and including October 6th. Velocities ranged from about 3.5 ft. per second to rather less than 0.5 ft. per second, and the experiments were generally repeated several times for each velocity. On October 18th the flow was changed to the north pipe, tuberculated, and this pipe was experimented upon with the same series of velocities as the south pipe.

The north pipe was cleaned November 12th, 13th, 14th and 15th by removing the tubercles completely from the interior. A photograph was then taken of the surface as cleaned (see Plate IX). It was found possible to remove tubercles without injuring materially the original coating underneath them, and, as will be seen by an examination of Plate IX, the original condition of the pipe was practically restored. The tubercles generally had central points or very small spots of attachment to the iron of the pipes. At these points the coating was lacking of course; but around them the tubercles spread over the surface of the coating, which remained in fair condition beneath. The original capacity of the pipe to pass water under a given head was nearly restored, the increase amounting to 30% at ordinary velocities. This was accomplished at small expense. There were 22 619 sq. ft. of surface scraped, swept and cleaned, with 57 days' labor, the space cleaned per man per day being 396 sq. ft. of surface, or about 32 lin. ft. of pipe. The labor was subdivided as follows: 32 days scraping tubercles; 21 days sweeping and washing the



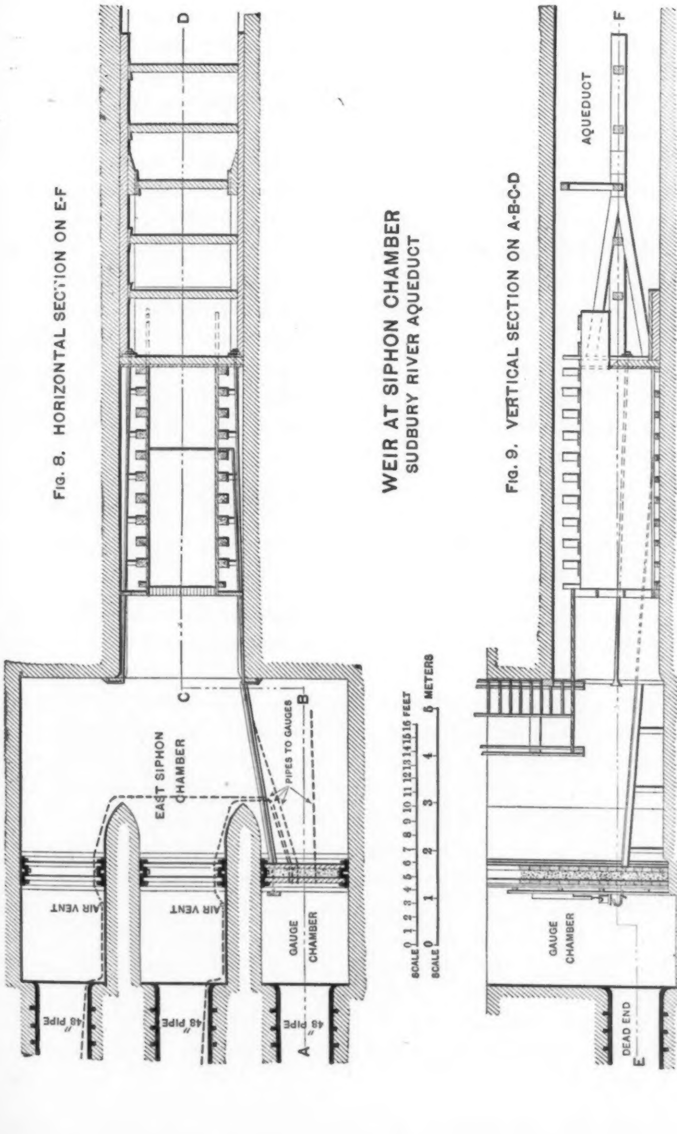


Fig. 8. HORIZONTAL SECTION ON E-F

WEIR AT SIPHON CHAMBER
SUDBURY RIVER AQUEDUCT

Fig. 9. VERTICAL SECTION ON A-B-C-D

pipe, and 4 days wheeling material. The scraping for a width of 2 ft. at the bottom was done with old round-pointed iron shovels; for the rest of the pipe with wooden scrapers made of oak, great care being taken not to disturb the tar coating. About two cart-loads of tubercles were taken out, beside what was flushed out of the blow-offs.

Beginning on November 30th, the experiments were continued on the cleaned north pipe at velocities ranging from 3.6 to less than 0.5 ft. per second. Early in November the terminal chamber weirs were erected and compared with the siphon weir (see Table No. 5), after which the siphon weir was removed and experiments were resumed on the cleaned north pipe, and extended to velocities of 7.25 ft. per second, which was the largest amount of water that it was practicable to pass through one pipe. On January 23d, 1895, the experiments at high velocities on the south pipe, tuberculated, were completed, but it was found practicable only to carry these velocities to 5.5 ft. per second.

The piezometer observations are recorded in Tables Nos. 3 and 4, the former including those piezometers only which were screwed into the sides of the pipes, and the latter the tube piezometers lying on the bottom of the pipes.

Measuring Apparatus at the Siphon Chambers.—The siphon chambers, as may be seen in Figs. 2, 4, 8 and 9, are built so that a third 48-in. pipe can be added in the future. It was determined to use the compartments provided for this third pipe as gauge chambers. They were made perfectly tight by means of double sets of stop-planks with puddle filling. The tube gauges were led into these compartments, and in the case of the east siphon chamber a pipe from the weir was carried into the same compartment to a small gauging box to which a hook-gauge was adjusted. Great care was taken to have these pipes rise by uniform grades to their gauges, and, where a summit was unavoidable, to put in a vent pipe carried above the water-level. In this way serious errors, which are often made in the readings of piezometers and weir gauges, due to collections of air, were avoided. The lengths of pipe under observation were 1 748.1 ft. of the north pipe and 1 747.96 ft. of the south pipe, those being the distances, referred to the axes of the pipes, between the middle points of the brass tubes.

Piezometers.—The piezometers that were screwed into the pipe from the outside were arranged in the following manner: A point was selected at the west end of the siphon sufficiently remote from the entrance of the pipe to allow the water to attain regular motion. This was 151.41 ft. from the upper end of the pipe. The east piezometers were inserted at 38.07 ft. from the lower end. The distance between these points, measured along the axis of the pipe, was 1 615.7 ft. Four openings were made in each pipe at each of these points (sixteen

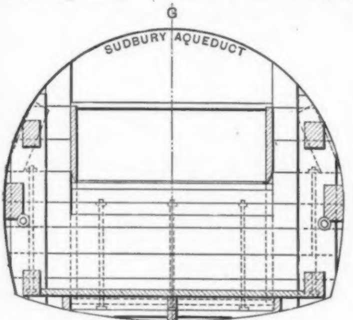


FIG. 10. DOWN-STREAM ELEVATION OF WEIR

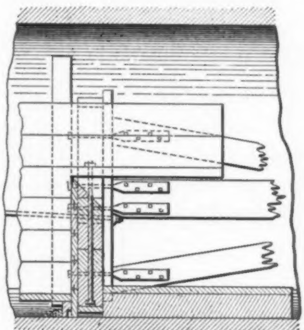


FIG. 11. VERTICAL SECTION ON G H

SCALE 0 1 2 3 4 5 6 FEET

SCALE 0 1 2 METERS

DETAILS OF
WEIR AT SIPHON CHAMBER

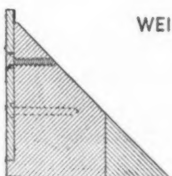


FIG. 12. VERTICAL SECTION THROUGH CREST

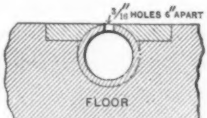


FIG. 13. BRASS PIPE 6 FT. BACK FROM CREST

SCALE 0 1 2 3 4 INCHES

SCALE 0 1 2 3 4 5 6 7 8 9 10 CENTIMETERS

holes in all), and as the welfare of the city depended upon the maintenance of the flow, sleeves were first put around the pipes where the holes were to be made. A tool was devised by which 3-in. holes were bored through the sleeve and pipe at the four points of section, as shown in Fig. 5.

Into these holes piezometers were inserted and secured, so that the axes of the tubes were at right angles to the direction of the flow.

These connections were accurately finished to the curvature of the pipe. They can be distinguished in Plate VIII, Fig. 2. The incrustation was removed from the interior of the pipe around the place of attachment, so that this portion of the surface was smooth. Into the outsides of these piezometer connections 1-in. corporation cocks were fitted to which lead pipes were soldered. These lead pipes from opposite sides of the 48-in. pipes were connected in pairs and then carried to the gauges, which were conveniently located for reading the extreme variations of head, and were provided with shelters for the observers. Care was taken to have no summits or depressions on these pipes.

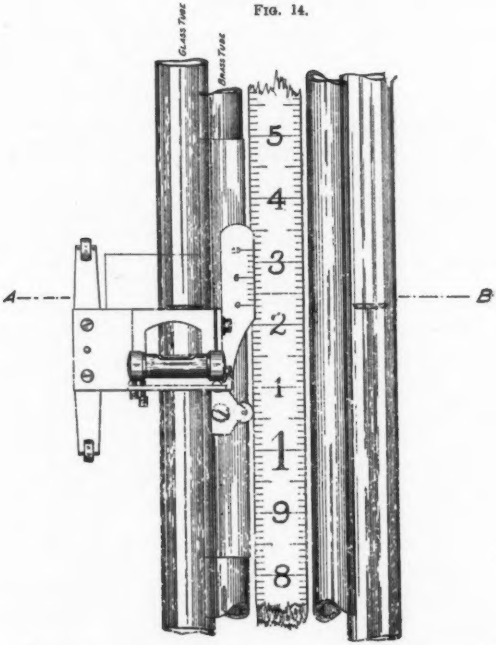
Tube Piezometers.—The tube piezometers which lay in the pipes were of $\frac{5}{8}$-in. brass tubes, pierced by 14 $\frac{3}{16}$-in. holes, spaced 6 ins. apart on centers. The tubes were closed with pointed oak plugs and were secured to the bottoms of the pipes and the spaces about the tubes filled with Portland cement.

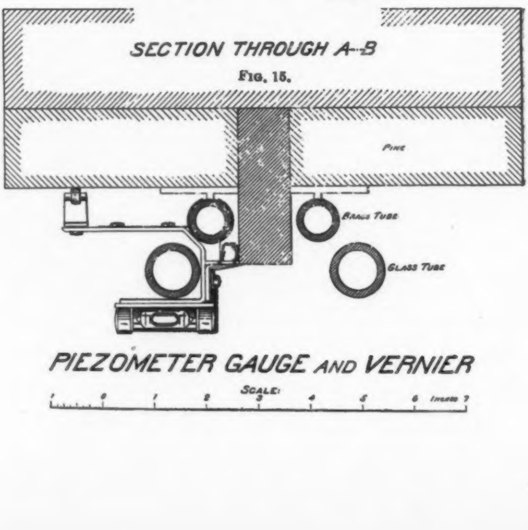
Gauges.—Each shelter contained a gauge arranged as shown in Figs. 14 and 15. This gauge was set for reading the two glass tubes containing the water columns, which were about 1 in. in internal diameter. These glass tubes could be connected with the lead pipes from either of the 48-in. pipes as desired. Behind the glass tubes were brass pipes for the verniers to slide upon. The scales were specially graduated by Gurley, and the verniers were made by Buff & Berger. The readings were recorded to thousandths of a foot. The lead pipes were furnished with stop and waste cocks, both at the connections with the 48-in. pipes and at the bottoms of the gauges, so that the observers could frequently test the water columns, to make sure that they were free from obstructions.

Weir at the Siphon.—The general arrangement of the weir at the siphon with details is shown in Figs. 8, 9, 10, 11, 12 and 13. It was 5 ft. long, 3.04 ft. high and approached by a channel 16 ft. long. It was securely built into the aqueduct and was tied by iron rods to the gate-chamber, so that it could not move, and was braced with heavy timbers on the down-stream side. It was provided with a screen to smooth the approach of the water to the weir. The head was read at a point 6 ft. above the crest by means of a brass tube laid across the channel of approach, laid flush with the bottom and

ELEVATION

Fig. 14.





SECTION THROUGH A–B

Fig. 15.

PIEZOMETER GAUGE AND VERNIER

SCALE:

1 0 1 2 3 4 5 6 Inches 7

pierced with $\frac{3}{16}$-in. holes 6 ins. apart, smoothly finished, and connected with the measuring chamber as already described. A blow-off cock at the gauge, which was frequently opened, prevented accumulations of air.

Careful measurements of the weir were made before each experiment, and changes in form, due to swelling or distortion, were noted. This is necessary in the case of a wooden weir, for, even with the best of workmanship, changes are constantly occurring. Fig. 7 shows an improved apparatus for comparing the level of the weir with the hook gauge. The method is the same as that used by Messrs. Fteley and Stearns in their weir experiments, but the apparatus has been made more convenient by the special arrangements shown. The hook is first adjusted by a delicate spirit level to the level of the crest, the sliding tin box is then brought up under the hook, the cock opened and an approximate adjustment made of the water surface to the level of the hook, which is made complete by a slow-motion screw; the elevation can then be read at once at the hook gauge at the other end of the pipe without waiting for wave motions to subside.

Weirs at the Terminal Gate Chamber.—The Sudbury Aqueduct terminates at Chestnut Hill Reservoir with a large stone chamber provided with five compartments controlled by gates and stop-planks, and conducting the water into the reservoir or into other connections. The two west compartments connect with the reservoir. In these, two weirs were built, and the other connections were dammed off by clay dams made perfectly tight. The west weir had a length of 5.84 ft., and the east weir 6.32 ft. They were both at the same level and 3.65 ft. high. The position of these weirs with reference to the flow in the aqueduct was peculiar. But satisfactory results were obtained by extensive screening and the use of a liberal amount of brush compactly placed, as shown in Figs. 16 and 17. The sheets of water passing over these weirs, with the largest quantities flowing, were not perfectly smooth, but very nearly so.

Comparative Observations between the Siphon and Terminal Chamber Weirs.—The flow in the aqueduct was adjusted at 3 o'clock P. M. for the amount of water required, and at 10 o'clock the next morning, when the water was flowing uniformly throughout the length of the aque-

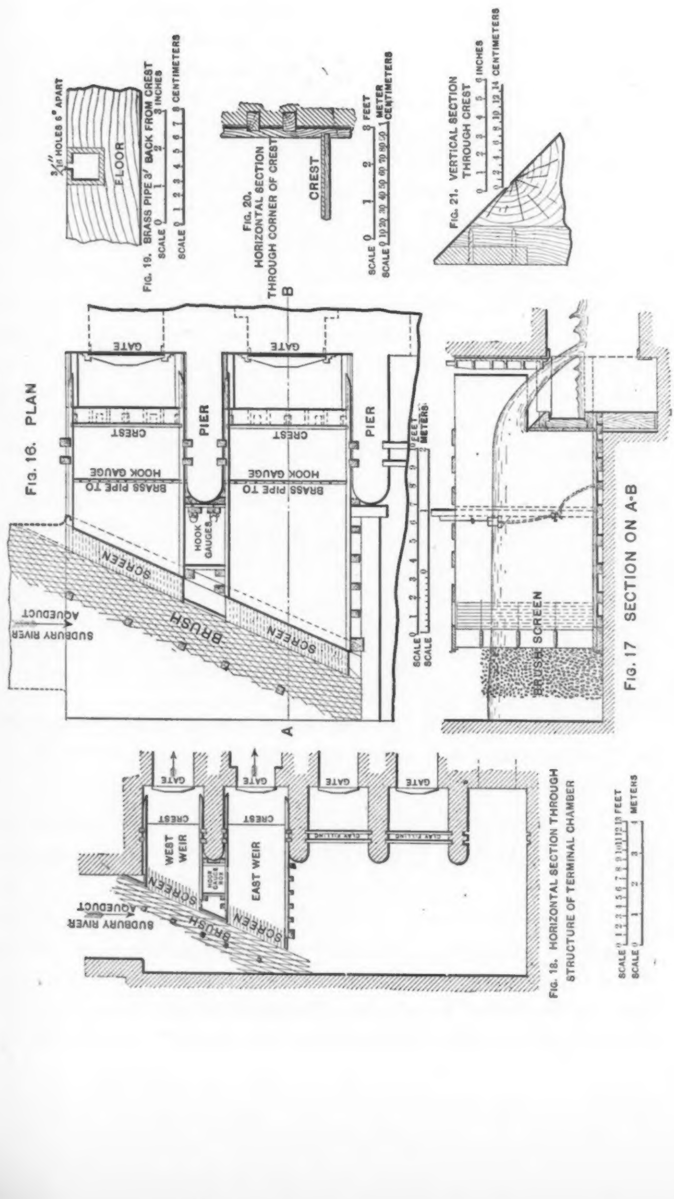


FIG. 16. PLAN
GATE
CREST
PIER
HOOK GAUGE
BRASS PIPE TO
HOOK GAUGES
SCREEN
BRUSH
SUDBURY RIVER AQUEDUCT
A
B
FEET
METERS
FIG. 17 SECTION ON A-B
BRUSH SCREEN
FIG. 18. HORIZONTAL SECTION THROUGH STRUCTURE OF TERMINAL CHAMBER
WEST WEIR
EAST WEIR
FIG. 19. BRASS PIPE 3' BACK FROM CREST
3/16" HOLES 6" APART
FLOOR
INCHES
CENTIMETERS
FIG. 20. HORIZONTAL SECTION THROUGH CORNER OF CREST
CREST
METER
FIG. 21. VERTICAL SECTION THROUGH CREST
SCALE

duct, the experiments were begun at the siphon chamber and were continued until 2.40 P. M.

In order to ascertain the time required for the water to pass from the weir at the siphon to the weirs at the terminal chamber, floats were put into the water below the siphon weir at regular intervals. They were received at the terminal chamber at intervals corresponding almost exactly. Accordingly, observations at the terminal weirs were regularly begun when the proper time had elapsed after the beginning of the siphon observations, and they were continued for the same length of time as at the siphon.

During the comparative observations care was taken not to disturb the gates at the head of the aqueduct, for it has been found that while it takes more than eight hours for the water to travel the length of the aqueduct, the slightest disturbance at the head gates sends an advance wave along the aqueduct with great rapidity. If one of these waves starts from the head of the aqueduct at the same time that a float is put into the aqueduct at the siphon chamber, the wave overtakes the float before it arrives at the terminal chamber. That is to say, the wave travels through 17 miles of aqueduct in less time than the water passes along the last 5 miles.

Table No. 5 shows the comparisons made between the weirs at siphon and terminal gate-chambers.

The mean ratio of the discharge (Q) at the siphon weir to the discharge (Q) at the terminal chamber was 0.9886, and all the discharges found at the terminal chamber were reduced to the standard of the siphon weir by the use of that ratio.

Leakage into the Aqueduct.—The leakage into the 5 miles of aqueduct was determined by weir measurements, and was found to amount to 0.558 cu. ft. per second.

Levels.—The zeros of the gauges were set by very careful spirit leveling, the probable error by least squares being 0.002 ft. in the distance of 1 800 ft.

Water Level Observations.—As a check on the spirit leveling the 48-in. pipes were alternately filled with water and shut off, so that the flow was stopped, and the elevations of the water surfaces were observed at both ends by reading the gauges. The readings at the two ends of the pipes were compared, and their differences were tabulated and plotted.

All the differences in the case of the tube piezometers and fully 75% in the case of the other piezometers were in the same direction, whence it was concluded that the zeros of the gauges had not been set at exactly the same level. Tables Nos. 6 and 7 give a summary of the comparison. It appears from Table No. 6, embracing the outside piezometers, that in the case of the north pipe, the zero of the scale at the west end was probably too low by 0.0019 ft., and that in the case of the south pipe it was too low by 0.0020 ft., relatively to the zeros at the east end.

From Table No. 7, it appears that the zeros of the west tube gauge piezometers were likewise too low by 0.0083 ft. in the case of the north pipe, and by 0.0065 ft. in the case of the south pipe. These gauges had not been set with as great care as the outside piezometer gauges.

By the method of least squares it was found that the difference in elevation between water surfaces at piezometer gauges could be determined from the means of all the water-level observations with a probable error much smaller than the probable error in the spirit leveling. This is owing to the very large number of readings of the water level. A close analysis of them convinced the author that their mean could be relied upon within 0.001 ft.

In the tables the values c_1 and c_3 have been calculated upon the basis of the spirit leveling. In order to substitute the relation determined by the water-level observations, it is necessary to make a slight correction. The values as corrected are given in the tables, and marked c_2 and c_4. For ordinary velocities their difference from c_1 and c_3 is insignificant. The diagrams (Figs. 22 and 23) have been plotted, using the values of c_2 and c_4.

Oscillations in the Isolated Pipes.—The comparisons of the water-level observations just mentioned were noticeably different for different times. To account for these differences, it was suggested that the effect of the wind might cause a difference in the pressure of the atmosphere between the two ends of the pipe. If atmospheric differences existed, it was evident that a correction on that account should be applied to the observed losses of head in the flowing pipe.

It had been found that the two pairs of piezometers at the same section gave the same reading, and that, therefore, the use of either

pair alone was sufficient. Accordingly, while the tube on one side of the gauge continued to be used for a pair of piezometers in the flowing pipe, the tube on the other side of the gauge was connected with the still pipe. Observations on the latter were continued during a large portion of the experimenting; and, as it was assumed that the same variations in atmospheric pressure were acting upon both pipes, it was intended that the results of each 100 minutes' observations of the flow should be corrected by an amount determined by the simultaneous observations on the still pipe. The comparative observations, however, did not afford a basis for making the corrections as contemplated.

There appeared to be no correspondence between the variations in the differences of water level and the variations in the velocity and direction of the wind. Moreover, for the same interval of time the difference of the readings on one set of gauges was often very different from that on the other set of gauges, and was opposite in direction in somewhat less than 25% of the observations of the outside piezometers.

The variations in question appeared to be due to an oscillating movement of the water in the pipe. The period of oscillation in the 48-in. pipe, if 1 800 ft. long, was found by calculation to be 33 seconds, neglecting the effects of friction. The observed period, being affected by friction, was from 60 to 70 seconds. The effect of the oscillations of the water in the pipe was shown on diagrams plotted from special readings made for the purpose on October 6th, 1894. It was seen from these plots that while an observer at one end of the pipe was reading the crest of the wave, the observer at the other end was reading the hollow, and that the period of oscillation was so nearly one minute that readings taken at intervals of two minutes did not give the mean position of the water surface; and it was at intervals of two minutes that the readings were taken during all of the observations in the tube piezometers, and on about half of the experiments on the other piezometers.

Correct results in such cases can only be obtained by taking the observations so often as to nullify the effect of the oscillations, which is often impracticable. The error was much smaller in the case of the readings taken every half minute, which almost eliminated the effect of the oscillations. The amplitude of the oscillations, as determined

in the piezometric readings, was, of course, modified by the throttling at the gauges. It was found that at the open end of the east end of the 48-in. pipe the amplitude was about 0.03 ft., while at the east piezometer it was 0.005 ft. If any correction were to be applied on account of the oscillation, it would, as above seen, be very small, and it would not be well worth making where there exists an uncertainty nearly as great arising from other causes.

It was found by experiment that readings of gauges similar to those used for the tube piezometers at the siphon are uncertain to the extent of 0.002 ft., probably due to variations in capillary attraction in the ½-in. glass tubes. The outside piezometer gauges had larger glass tubes. It further appeared from an actual test, continued throughout a whole day, that there is a liability to errors of observation in the case of the piezometric readings amounting to 0.001 ft., and to somewhat more than that in the case of the tube piezometers, which were unprovided with verniers. Four series of observations of 100 minutes each were made. There were four observers employed, two at each of the two piezometer gauges, and they changed ends several times during the day. One observer read the column on one side of the gauge, and the other, that on the other side. Readings were taken every half minute, the observers reading simultaneously for half the day, and alternately at quarter-minute intervals the other half day. The differences of one observer from the other on the mean of 100 minutes were 0.0003, 0.0006, 0.0003, 0.0003, 0.0006, 0.0001, 0.0013 and 0.0013.

The author has gone into this matter fully, not so much on account of its value in determining the coefficients, as for the purpose of showing the refinements to which these experiments were carried, and pointing out what perplexing sources of error are liable to be encountered in such work. In ordinary experiments to determine the losses of head it would be unnecessary to go to the expense of such fine apparatus.

Degree of Accuracy in Measurements and Results.—The approximate uniformity of the piezometric readings can be seen by a study of the tables, which give the highest and lowest readings in the different 20-minute intervals, with the range, which is generally less than 0.02 ft.

The length of the pipe has probably been obtained with a precis-

ion of 1 in 50 000, which is 0.002%, and would equal about 0.03 ft. in a length of 1 600 ft.

The accuracy of the leveling and of the reading of the gauges has already been discussed. Upon these elements the accuracy of the determination of the loss of head depends.

The measurement of the discharge is probably liable to an error of 1%, and, as the velocities vary directly as the discharge, the velocity is liable to an error of 1%, or, say, from an error of 0.003 ft. per second for the smallest velocity to 0.07 ft. per second for the largest. The coefficient c is in error about 1% if the velocity is in error 1 per cent.

Formula for Weirs.—Much study was given to the question what formula to use in computing the discharge of the weirs, and it was finally decided to use the result of Bazin's experiments, as best fitting the case in hand. The formula is $Q = m\, L\, H \sqrt{2gH}$. The values of the coefficient m for each height of weir employed were tabulated from the results of Bazin's experiments and used in the computations.

Notation.—Quantities entering into the formulas are expressed as follows when English measures are used:

I = friction head in feet per foot of pipe.
v = mean velocity in feet per second.
R = hydraulic mean depth in feet.

Formula for Flow in Pipes.—For the want of any really satisfactory formula to express the law of flow in pipes generally, the familiar Chézy formula, $v = c\,(R\,I)^{\frac{1}{2}}$ has been made the basis of study for these experiments. In the pipes in question, the diameter being 4 ft., $R = 1$ and vanishes, so that the formula becomes $v = c\,I^{\frac{1}{2}}$. It being impossible to assign to c in that formula any one value which will fit all cases, the attempt has been made to find what different values of c will fit the various conditions experimented upon.

Simple Chézy Formula Sufficient Only for Particular Condition of Surface of Pipe.—In the tuberculated pipes experimented upon, a constant value of 108 for c, making the formula $v = 108\,I^{\frac{1}{2}}$, fits the experiments well for all the heads. The form $v = 100\,I^{\frac{1}{2}}$ is still easier to remember, and is excellent to express the flow through 48-in. pipe

slightly more tuberculated, say with 20 years' service. For metric measures these formulas become $v = 59.63\ (R\,I)^{\frac{1}{2}}$ and $v = 55.21\ (R\,I)^{\frac{1}{2}}$, respectively. To fit the experiments on the clean pipe closely, however, different values of c are required for different heads.

The Substitution of Kutter's Coefficients Adapts the Formula to Different Cases and Particularly to Clean Pipe.—In substituting values for c the method of Kutter's formula is admirable in that it takes account separately of the different elements that modify the coefficient, to wit, the hydraulic mean depth, the loss of head and the condition of the surface as to roughness. The last is allowed for by the introduction of a quantity, represented by n, called the coefficient of roughness. This is of especial importance, it being found that the rusting of the interior of a pipe diminishes its capacity very much, as already stated in the case of the Rosemary siphon. In designing works a large allowance is necessarily made for this, if they are expected to last for many years. The coefficient c according to Kutter's formula fits well the experiments on the clean pipe, taking $n = 0.011$. The formula then becomes

$$v = \frac{206.2\ I + 0.00281}{1.458\ I + 0.000031} \times I^{\frac{1}{2}}.$$

To fit the experiments on the tuberculated pipe as nearly as possible with Kutter's formula, n should be taken about 0.014, which is about the same value that he uses for brickwork. The formula then becomes

$$v = \frac{171\ I + 0.00281}{1.582\ I + 0.0000393} \times I^{\frac{1}{2}}.$$

To fit what the author believes would be the condition of a pipe badly tuberculated, say by fifty years' service, n in Kutter's formula should be taken as large as 0.0157, and the formula would be

$$v = \frac{157\ I + 0.00281}{1.653\ I + 0.0000441} \times I^{\frac{1}{2}}.$$

This formula is not based on experiment.

In the case of the tuberculated pipes the Kutter formula does not fit the low heads, say for velocities of less than 1 ft. per second. At low velocities the loss of head due to friction is very small and difficult to measure with accuracy relatively to the magnitudes involved.

Hence the probable error is relatively large, and at the best the precise form of the curve which would graphically express c is doubtful for very low heads. As n is the coefficient of roughness, it was intended that the same value should be assigned to it in a pipe in any one given state, irrespectively of whether the velocity of the water running through it is great or small; an idea of the imperfection of the Kutter formula if applied to these experiments may therefore be obtained from the statement that instead of 0.014, as above mentioned for the value of n for considerable velocities, it would be necessary in the case of the Rosemary south pipe, in order to fit the Kutter formula for the velocity of 1.2 ft. per second, to make n about 0.013, and for the velocity of 0.7 ft. per second, about 0.012.

Formula Chosen for the Present Investigation.—It was found that for the author's experiments an exponential formula would fit the case of the tuberculated pipe much better, and of the clean pipe somewhat better than Kutter's formula.

The desired formula was obtained by the method of logarithmic homologues described by Professor Reynolds in the *Philosophical Transactions* of the Royal Society, London, 1883. The logarithms of I were plotted as abscissas, and the logarithms of v as ordinates; and from drawing straight lines, coinciding as nearly as possible with the plotted points on these logarithmic diagrams, exponents were obtained from which the following formulas are derived:

	North Pipe.		South Pipe.
	Cleaned.	Tuberculated.	Tuberculated.
v................	$166\ I^{\frac{1}{1.91}}$	$99.5\ I^{\frac{1}{2.03}}$	$105.4\ I^{\frac{1}{2.02}}$
v, feet...........	$170\ I^{\frac{1}{1.9}}$	$108\ I^{\frac{1}{2}}$	
v, meters........	$93.86\ I^{\frac{1}{1.9}} R^{\frac{1}{2}}$	$59.63\ I^{\frac{1}{2}} R^{\frac{1}{2}}$	

The expressions in the last two lines are obtained by rounding off figures for greater simplicity; they might be used as the basis for computing tables if desired.

The curves plotted on the diagrams of c, Figs. 22 and 23, are based on calculation from formulas given in the first line of the preceding table.

Experiments of Mr. Stearns.—The experiments recorded in this paper possess an additional value from the fact that the coefficients for the same pipes when new were determined by F. P. Stearns, M. Am. Soc. C. E., as communicated to this Society in his paper read October 1st, 1884.*

By the three experiments which Mr. Stearns regarded as trustworthy the coefficient c in the Chézy formula, $v = c\,(R\,I)^{\frac{1}{2}}$ had values as shown in the second column of the table below, for the velocities given in the first column respectively. The corresponding coefficients as determined by the experiments of 1894–95 in the clean pipe (tubercles removed) calculated by the formula $c = 131.88\ v^{0.045}$ (the same value used in formula 166 $I^{\frac{1}{1.91}}$), are given in the third column.

Velocity.	c, 1880.	c, 1894–95.
3.738	140.14	139.94
4.965	142.11	141.74
6.195	144.09	143.16

Conclusion.—In referring to the number of years of service of pipes as indicative of the condition of the interior surface, it should be observed that in other localities the effect of use may not be the same as on the Boston Water-Works. Many waters, for example, containing lime produce a smooth white coating inside the pipes. It is greatly to be desired that more accurate observations and experiments should be made as to how the frictional loss of head is affected by such coating, and whether it becomes further modified by longer periods of service.

The results herewith presented led the author to the conclusion that piezometric gauges laid upon the bottom of a pipe and those screwed into the sides give equally accurate results and that these piezometers when properly arranged can be depended upon as certainly as can other hydraulic appliances of precision. The author is particular in calling attention to this fact on account of slurs

* See the *Transactions* of the American Society of Civil Engineers, Vol. xiv, p. 1.

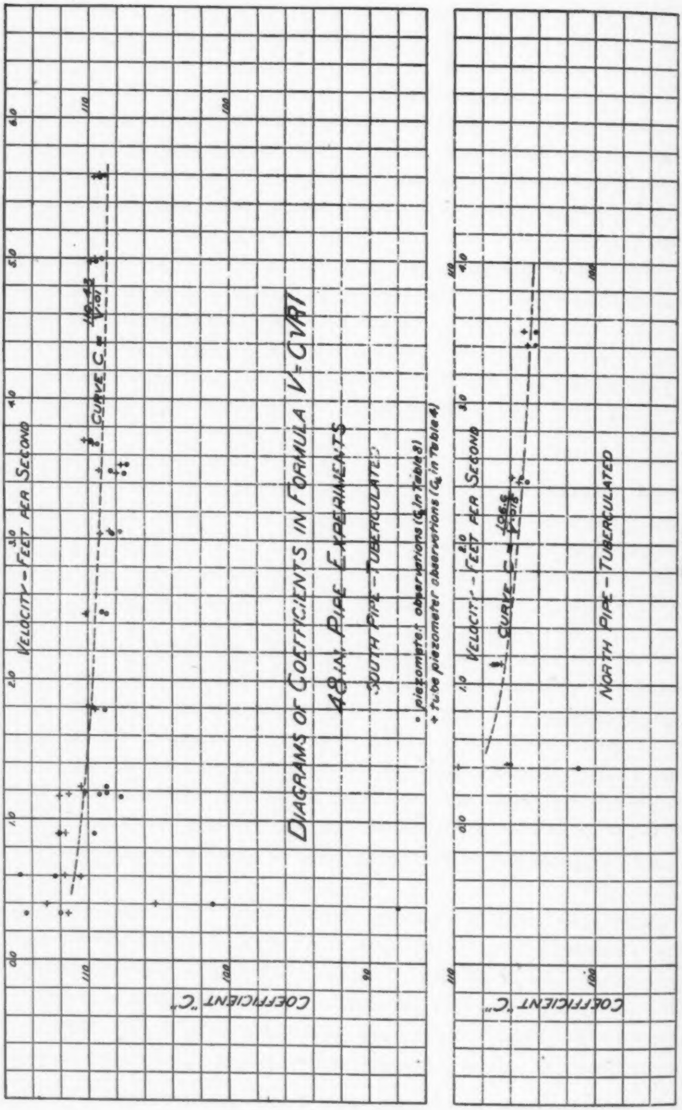

DIAGRAMS OF COEFFICIENTS IN FORMULA V=C√RI
48 IN. PIPE EXPERIMENTS
SOUTH PIPE - TUBERCULATED
NORTH PIPE - TUBERCULATED
VELOCITY - FEET PER SECOND
COEFFICIENT "C"

Fig. 22.

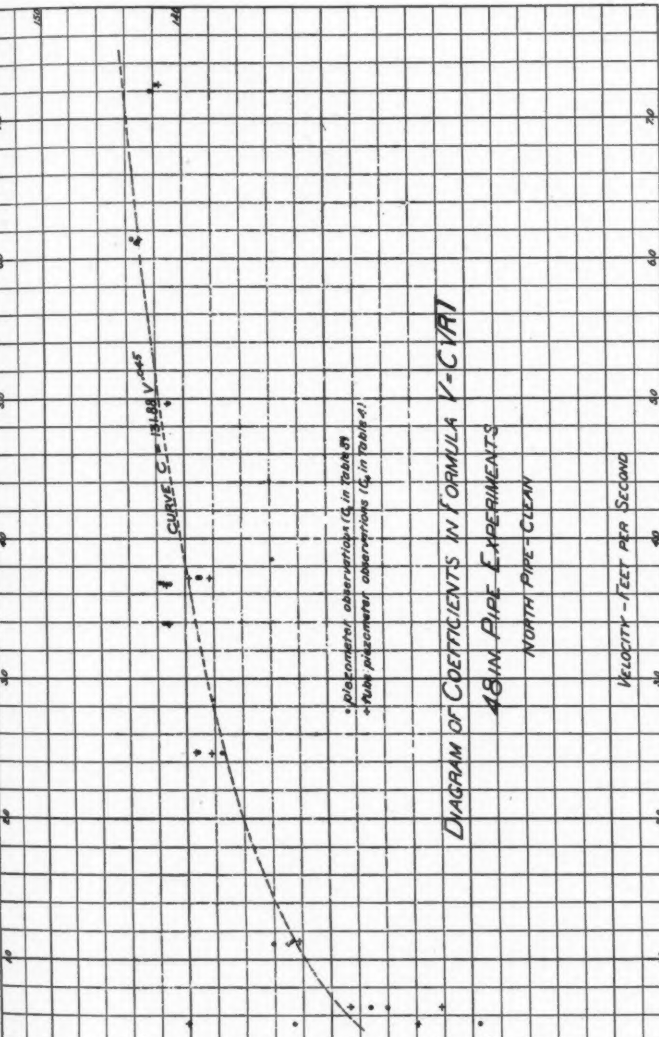


Diagram of Coefficients in Formula V=C√RI
48 in. Pipe Experiments
North Pipe-Clean
Velocity-Feet per Second
Coefficient "C"

Fig. 23.

that have been cast by some hydraulicians upon piezometric observations.

In conclusion the author desires to express his obligations to Messrs. William E. Foss, Frank S. Hart and F. F. Moore, principal assistants in these experiments, to whose skill and zeal the success of the work is largely due, and to Fred. Brooks, M. Am. Soc. C. E., for advice in the preparation of this paper.

TABLE No. 1.—WEIR OBSERVATIONS (Terminal Chamber).

Using Bazin's values of m in formula $Q = m\ L\ H\ \sqrt{2\ g\ H}$; $g = 32.17$.

Experiments 216 or XLIV to LI were on north pipe clean ; LI to LVI, inclusive, on south pipe tuberculated (see note to Table No. 2).

1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
				East Weir.								West Weir.										
				Height of water on weir.								Height of water on weir.										
Date.	Number of experiment.	Time of beginning.	Time of ending.	No. observations.	Highest. Feet.	Lowest. Feet.	Range. Feet.	Mean. H. Feet.	Mean length of weir. L. Feet.	Coefficient from table. m.	Quantity in cubic feet per second. Q.	No. observations.	Highest. Feet.	Lowest. Feet.	Range. Feet.	Mean. H. Feet.	Mean length of weir. L. Feet.	Coefficient from table. m.	Quantity in cubic feet per second. Q.	Total quantity. Column 11 plus column 19.	Total quantity, less 0.558 cubic feet per second, leakage.	Column 21. x 0.9886 to reduce to siphon weir.
1894.																						
Dec. 24th.	216	1.00	1.20	10	1.5081	1.5040	0.0041	1.5057	6.3244	0.4322	40.509	11	1.5265	1.5214	0.0051	1.5228	5.8403	0.4324	38.065	78.574	78.016	77.127
" 24th.	217	1.20	1.40	10	1.5070	1.5029	0.0041	1.5052	6.3244	0.4322	40.489	11	1.5262	1.5219	0.0043	1.5240	5.8403	0.4324	38.110	78.599	78.041	77.151
" 24th.	218	1.40	2.00	10	1.5072	1.5032	0.0040	1.5055	6.3244	0.4322	40.501	11	1.5272	1.5203	0.0069	1.5243	5.8403	0.4324	38.121	78.622	78.064	77.174
" 24th.	219	2.00	2.20	10	1.5090	1.5035	0.0055	1.5068	6.3244	0.4322	40.553	11	1.5275	1.5203	0.0072	1.5236	5.8403	0.4324	38.095	78.648	78.090	77.200
" 24th.	220	2.20	2.40	10	1.5083	1.5034	0.0049	1.5062	6.3244	0 4322	40.529	11	1.5250	1.5210	0.0040	1.5231	5.8403	9.4324	38.076	78.605	78.047	77.157
	(XLIV)	1.00	2.40	50	1.5090	1.5029	0.0061	1.5059	6.3244	0.4322	40.517	51	1.5275	1.5203	0.0072	1.5236	5.8403	0.4324	38.095	78.612	78.054	77.164
Dec. 24th.	(XLV)	4.20	6.00	50	1.5065	1.4989	0.0076	1.5032	6.3244	0.4322	40.408	51	1.5240	1.5171	0.0069	1.5207	5.8403	0.4324	37.986	78.394	77.836	76.949
1895.																						
Jan. 10th.	(XLVI)	2.40	4.20	51	1.0903	1.0854	0.0049	1.0876	6.3206	0.4285	24.641	50	1.1061	1.1001	0.0060	1.1029	5.8367	0.4286	23.242	47.883	47.325	46.785
" 10th.	(XLVII)	6.00	7.40	51	1.0940	1.0841	0.0099	1.0875	6.3206	0.4285	24.637	50	1.1091	1.0996	0.0095	1.1030	5.8367	0.4287	23.250	47.887	47.329	46.789
" 11th.	(XLVIII)	2.30	4.10	51	1.3168	1 3073	0.0095	1.3133	6.3200	0.4304	32.838	50	1.3337	1.3259	0.0078	1.3304	5.8364	0.4306	30.934	63.772	63.214	62.493
" 16th.	(XLIX)	2.00	3.40	51	1.6728	1.6660	0 0068	1.6692	6.3185	0.4338	47.414	50	1.6956	1.6866	0.0090	1.6914	5.8354	0.4340	44.686	92.100	91.542	90.498
" 16th.	(L)	5.20	7.00	51	1.6790	1.6718	0.0072	1.6761	6.3184	0.4339	47.719	50	1.7014	1.6931	0.0083	1.6972	5.8354	0.4341	44.926	92.645	92.087	91.037
" 23d .	(LI)	2.40	4.20	51	1.0770	1.0715	0.0055	1.0744	6.3207	0.4284	24.188	50	1.1026	1.0965	0.0061	1.0995	5.8367	0.4286	23.134	47.322	46.764	46.231
" 23d .	(LII)	6.00	7.40	51	1.0864	1.0740	0.0124	1.0792	6.3207	0.4285	24.356	50	1.1111	1.1003	0.0108	1.1041	5.8367	0.4287	23.285	47.641	47.083	46.546
" 24th.	(LIII)	2.30	4.10	51	1.3120	1.3030	0.0090	1.3077	6.3200	0.4303	32.621	50	1.3436	1.3351	0.0085	1.3391	5.8364	0.4306	31.238	63.859	63.301	62 579
" 24th.	(LIV)	5.50	7.30	51	1.3174	1.3065	0.0109	1.3117	6.3200	0.4304	32.778	50	1.3461	1.3379	0.0082	1.3428	5.8364	0.4307	31.375	64.153	63.595	62.870
" 25th.	(LV)	2.20	4.00	51	1.4120	1.4048	0.0072	1.4078	6.3197	0.4313	36.520	50	1.4444	1.4385	0.0059	1.4409	5.8362	0.4316	34.946	71.466	70.908	70.100
" 25th.	(LVI)	5.40	7.20	51	1.4152	1.4045	0.0107	1.4099	6.3197	0.4313	36.602	50	1.4472	1.4391	0.0081	1.4429	5.8362	0.4316	35.019	71.621	71.063	70.253

NOTE.—The temperatures during the experiments were as follows: 216, 36.7°; XLV, 36.8; XLVI, 37°; XLVII, 37°; XLVIII, 36.7°; XLIX, 35.5°; L, 35.3°; LI, 35.5°; LIII, 35.1°; LV, 34.9°.

TABLE No. 2. WEIR OBSERVATIONS (Siphon).*

Using Bazin's values of m in formula $Q = m\ L\ H \sqrt{2\,g\,H};\ g = 32.17$.

Experiments 1 or I to XXII were on the tuberculated south pipe, XXII to XXX on the north pipe tuberculated, and XXX to XLIV on the north pipe clean.

1	2	3		4	5	6	7	8	9	10	11	12
				HEIGHT OF WATER ON WEIR.								
Date.	Number of experiment.	Time of beginning.	Time of ending.	Number of observations.	Highest. Feet.	Lowest. Feet.	Range. Feet.	Mean. H. Feet.	Mean length of weir. Feet. L.	Coefficient from table. m.	Quantity in cubic feet per second. Q.	Temperature of water, Fahrenheit.
1894. September 4th. P.M..	1	1:20	1:40	10	1.8438	1.8277	0.0161	1.8347	4.9707	0.4421	43.805	64.2°
	2	1:40	2:00	11	1.8420	1.8302	0.0118	1.8368	4.9707	0.4422	43.890	
	3	2:00	2:20	11	1.8399	1.8332	0.0067	1.8368	4.9707	0.4422	43.890	
	4	2:20	2:40	11	1.8385	1.8356	0.0029	1.8372	4.9707	0.4422	43.905	
	5	2:40	3:00	11	1.8390	1.8358	0.0032	1.8375	4.9707	0.4422	43.916	
	(I)	1:20	3:00	50	1.8438	1.8277	0.0161	1.8366	4.9707	0.4422	43.883	
1894. September 5th. A.M..	(II)	10:00	11:40	51	1.4778	1.4700	0.0078	1.4740	4.9712	0.4373	31.205	66.2°
" 5th. P.M..	(III)	1:20	3:00	51	1.4710	1.4640	0.0070	1.4674	4.9712	0.4372	30.989	
" 6th. A.M..	(IV)	10:00	11:40	51	0.9143	0.8990	0.0153	0.9050	4.9724	0.4303	14.776	
" 6th. P.M..	(V)	1:20	3:00	51	0.9029	0.8951	0.0078	0.8990	4.9725	0.4303	14.629	
" 7th. A.M..	(VI)	10:00	11:40	51	0.4475	0.4380	0.0095	0.4431	4.9746	0.4311	5.074	65.1°
" 7th. P.M..	(VII)	1:20	3:00	51	0.4400	0.4333	0.0067	0.4368	4.9747	0.4312	4.967	65.1°
" 11th. A.M..	(VIII)	10:00	11:40	51	1.6973	1.6785	0.0188	1.6858	4.9709	0.4401	38.409	70.3°
" 11th. P.M..	(IX)	1:20	3:00	51	1.6832	1.6763	0.0069	1.6798	4.9709	0.4401	38.204	70.3°
" 12th. A.M..	(X)	10:00	11:40	51	1.2058	1.1966	0.0092	1.2005	4.9717	0.4337	22.750	68.8°
" 12th. P.M..	(XI)	1:20	3:00	51	1.2036	1.1830	0.0206	1.1930	4.9717	0.4336	22.532	
" 13th. A.M..	(XII)	10:00	11:40	51	0.7775	0.7593	0.0182	0.7614	4.9732	0.4290	11.370	67.7°
" 13th. P.M..	(XIII)	1:20	3:00	51	0.7618	0.7525	0.0093	0.7590	4.9732	0.4290	11.316	
" 14th. A.M..	(XIV)	10:00	11:40	51	0.5900	0.5769	0.0131	0.5823	4.9740	0.4291	7.607	67.6°
" 14th. P.M..	(XV)	1:20	3:00	51	0.5796	0.5725	0.0071	0.5756	4.9740	0.4292	7.478	

October	4th. A.M..	(XVI)	10:00	11.40	51	1.8404	1.8170	0.0234	1.8302	4.9688	0.4421	43.628	61.4°
"	4th. P.M..	(XVII)	1:20	3.00	51	1.8595	1.8406	0.0189	1.8510	4.9687	0.4424	44.403	
"	5th. A.M..	(XVIII)	10:00	11:40	51	0.9405	0.9263	0.0142	0.9312	4.9702	0.4306	15.426	61.8°
"	5th. P.M..	(XIX)	1:20	3:00	51	0.9174	0.9102	0.0072	0.9136	4.9702	0.4304	14.984	
"	6th. A.M..	(XX)	10:00	11:40	51	0.3922	0.3860	0.0062	0.3883	4.9728	0.4323	4.172	61.6°
"	6th. P.M..	(XXI)	1:20	3:00	51	0.4067	0.3777	0.0290	0.3845	4.9728	0.4324	4.112	
"	18th. A.M..	(XXII)	10:00	11:40	51	1.8172	1.8007	0.0165	1.8101	4.9688	0.4418	42.882	53.3°
"	18th. P.M..	(XXIII)	1:20	3:00	48	1.8564	1.8324	0.0240	1.8430	4.9687	0.4423	44.105	
"	19th. A.M..	(XXIV)	10 00	11:40	51	1.4732	1.4635	0.0097	1.4690	4.9692	0.4373	31.034	52.8°
"	19th. P.M..	(XXV)	1:20	3:00	51	1.4613	1.4545	0.0068	1.4575	4.9693	0.4371	30.657	
"	20th. A.M	(XXVI)	10:00	11:40	51	0.4568	0.4465	0.0103	0.4523	4.9724	0.4309	5.228	
"	20th. P.M..	(XXVII)	1:20	3:00	51	0.4445	0.4393	0.0052	0.4420	4.9724	0.4311	5.053	
"	30th. A M..	(XXVIII)	10:00	11:40	50	0.8897	0.8801	0.0096	0.8847	4.9703	0.4301	14.269	
"	30th. P.M..	(XXIX)	1:20	3:00	50	0.8894	0.8828	0.0066	0.8860	4.9703	0.4301	14.300	
November	30th. A M..	(XXX)	10:00	11:40	51	1.9035	1.8943	0.0092	1.8979	4.9693	0.4430	46.169	
"	30th. P.M..	(XXXI)	1:20	3:00	50	1.9053	1.8966	0.0087	1.9009	4.9693	0.4430	46.278	
December	1st. A.M..	(XXXII)	10:00	11:40	51	1.4751	1.4646	0.0105	1.4699	4.9700	1.4373	31.068	35.5°
"	1st. P.M..	(XXXIII)	1:20	3:00	51	1.4759	1.4641	0.0118	1.4714	4.9700	0.4373	31.115	
"	7th. A M..	(XXXIV)	10:00	11:40	51	0.8809	0.8672	0.0137	0.8731	4.9714	0.4300	13.989	36.5°
"	7th. P.M..	(XXXV)	1:20	3:00	51	0.8845	0.8765	0.0080	0.8808	4.9713	0.4301	14.177	
"	8th. A.M..	(XXXVI)	10:00	11:40	51	0.4391	0.4315	0.0076	0.4369	4.9735	0 4312	4.968	37.3°
"	8th. P.M..	(XXXVII)	1:20	3:00	51	0.4410	0.4325	0.0085	0.4387	4.9735	0.4312	4.998	
"	13th. A.M..	(XXXVIII)	10:00	11:40	51	1.8108	1.7878	0.0230	1.8009	4.9694	0.4417	42.551	36.5°
"	13th. P.M..	(XXXIX)	1:20	3:00	51	1.8113	1.7877	0.0236	1.8013	4.9694	0.4417	42.565	
"	14th. A.M..	(XL)	10:00	11:40	51	0.6225	0.6113	0 0112	0.6168	4.9727	0.4289	8.287	37.0°
"	14th. P.M..	(XLI)	1:20	3:00	51	0.6249	0.6071	0.0178	0.6148	4.9727	0 4289	8.247	
"	15th. A.M..	(XLII)	10:00	11:40	51	0.5483	0.5323	0.0160	0.5362	4.9730	0.4295	6.727	38.3°
"	15th. P.M..	(XLIII)	1:20	3:00	49	0.5430	0.5350	0.0080	0.5388	4.9730	0.4295	6.776	

* It was intended originally to print the tables in full, but on account of the space required they have been condensed. Each experiment, covering 20 minutes and embracing ten observations, was numbered as a distinct experiment with arabic figures. Five of these experiments, covering 100 minutes, were united and a mean obtained, forming a set of means designated by Roman numerals. The latter only have been printed, but with each table a sample of the whole method on which the table was formed is given to show the slight variations in the 20-minute experiments.

TABLE No. 3.—Piezometer Observations.

1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
				West Piezometer Readings.					East Piezometer Readings.										Results from columns 15 and 18 corrected for water levels.	
Date.	Number of experiment.	Time of beginning.	Time of ending.	Number of observations.	Highest. Feet.	Lowest. Feet.	Range. Feet.	Mean. Feet.	Number of observations.	Highest. Feet.	Lowest. Feet.	Range. Feet.	Mean. Feet.	Mean total fall in 1 615.7 feet of pipe. Feet.	Fall per foot of pipe I_1. Feet.	Discharge from table 1, column 11; and table 2, column 22. Cubic feet per second.	Mean velocity of flow in pipe, v. Feet per second.	Coefficient in $V = c_1 \sqrt{RI_1}$. c_1.	I_2.	c_2.
South Pipe Tuberculated.—Length, 1 615.70 Ft.																				
1894. Sept. 4th, P.M..	1	1.20	1.40	21	6.548	6.541	0.007	6.5438	21	4.877	4.865	0.012	4.8695	1.6743	0.0010363	43.805	3.486	108.29		
	2	1.40	2.0	21	6.549	6.542	0.007	6.5439	21	4.873	4.860	0.013	4.8669	1.6770	0.0010379	43.890	3.493	108.41		
	3	2.0	2.20	21	6.552	6.544	0.008	6.5484	21	4.873	4.858	0.015	4.8650	1.6834	0.0010419	43.890	3.493	108.20		
	4	2.20	2.40	21	6.554	6.548	0.006	6.5513	21	4.876	4.867	0.009	4.8721	1.6792	0.0010393	43.905	3.494	108.38		
	5	2.40	3.0	21	6.557	6.552	0.005	6.5541	21	4.877	4.868	0.009	4.8728	1.6813	0.0010406	43.916	3.495	108.33		
	(I)	1.20	3.0	101	6.557	6.541	0.016	6.5483	101	4.877	4.858	0.019	4.8693	1.6790	0.0010392	43.883	3.492	108.33	0.0010383	108.38
1894. Sept. 5th, A.M..	(II)	10.0	11.40	101	5.347	5.338	0.009	5.3431	101	4.509	4.497	0.012	4.5023	0.8408	0.0005204	31.205	2.483	108.86	0.0005195	108.96
" 5th, P.M..	(III)	1.20	3.0	101	5.337	5.330	0.007	5.3340	101	4.507	4.497	0.010	4.5006	0.8334	0.0005158	30.989	2.466	108.58	0.0005149	108.68
" 6th, A.M..	(IV)	10.0	11.40	101	5.345	5.340	0.005	5.3418	101	5.159	5.146	0.013	5.1530	0.1888	0.0001169	14.776	1.176	108.77	0.0001160	109.20
" 6th, P.M..	(V)	1.20	3.0	101	5.345	5.341	0.004	5.3432	101	5.159	5.149	0.010	5.1528	0.1904	0.0001178	14.629	1.164	107.24	0.0001169	107.66
" 7th, A.M..	(VI)	10.0	11.40	101	6.056	6.048	0.008	6.0513	101	6.026	6.023	0.003	6.0241	0.0272	0.0000168	5.074	0.404	98.40	0.0000159	101.23
" 7th, P.M..	(VII)	1.20	3.0	51	6.065	6.061	0.004	6.0617	51	6.031	6.026	0.005	6.0276	0.0341	0.0000211	4.967	0.395	86.04	0.0000202	88.00
" 11th, A.M..	(VIII)	10.0	11.40	51	6.026	6.003	0.023	6.0141	51	4.723	4.704	0.019	4.7133	1.3008	0.0008051	38.409	3.057	107.72	0.0008042	107.78
" 11th, P.M..	(IX)	1.20	3.0	51	5.998	5.975	0.023	5.9849	51	4.717	4.702	0.015	4.7108	1.2741	0.0007886	38.204	3.040	108.26	0.0007877	108.32
" 12th, A.M..	(X)	10.0	11.40	51	5.872	5.861	0.011	5.8681	51	5.438	5.419	0.019	5.4287	0.4394	0.0002720	22.750	1.810	109.78	0.0002711	109.97
" 12th, P.M..	(XI)	1.20	3.0	51	5.868	5.862	0.006	5.8641	51	5.433	5.414	0.019	5.4238	0.4404	0.0002726	22.532	1.793	108.60	0.0002717	108.79
" 13th, A.M..	(XII)	10.0	11.40	51	6.395	6.388	0.007	6.3921	51	6.287	6.284	0.003	6.2852	0.1069	0.0000662	11.370	0.905	111.23	0.0000653	112.02
" 13th, P.M..	(XIII)	1.20	3.0	51	6.398	6.391	0.007	6.3950	51	6.287	6.282	0.005	6.2844	0.1106	0.0000685	11.316	0.901	108.84	0.0000676	109.59
" 14th, A.M..	(XIV)	10.0	11.40	51	6.152	6.144	0.008	6.1484	51	6.106	6.100	0.006	6.1020	0.0464	0.0000287	7.607	0.605	112.96	0.0000278	114.83
" 14th, P.M..	(XV)	1.20	3.0	51	6.148	6.142	0.006	6.1453	51	6.101	6.097	0.004	6.0985	0.0468	0.0000290	7.478	0.595	110.57	0.0000281	112.39
Oct. 4th, A.M..	(XVI)	10.0	11.40	51	6.574	6.515	0.059	6.5465	51	4.868	4.848	0.020	4.8580	1.6885	0.0010451	43.628	3.472	107.39	0.0010442	107.44
" 4th, P.M..	(XVII)	1.20	3.0	51	6.655	6.617	0.038	6.6374	51	4.892	4.869	0.023	4.8815	1.7559	0.0010868	44.403	3.533	107.18	0.0010859	107.23

Oct. 5th, A.M..	(XVIII)	10.0	11.40	51	5.407	5.392	0.015	5.4008	50	5.204	5.184	0.020	5.1932	0.2076	0.0001285	15.426	1.228	108.30	0.0001276	108.69
" 5th, P.M..	(XIX)	1.20	3.0	51	5.382	5.372	0.010	5.3762	51	5.191	5.174	0.017	5.1803	0.1959	0.0001212	14.984	1.192	108.29	0.0001203	108.71
" 6th, A.M..	(XX)	10.0	11.40	51	6.026	6.017	0.009	6.0205	51	6.012	6.000	0.012	6.0054	0.0151	0.0000093	4.172	0.332	108.61	0.0000084	114.44
" 6th, P.M..	(XXI)	1.20	3.0	51	6.023	6.009	0.014	6.0129	51	6.005	5.983	0.022	5.9976	0.0153	0.0000095	4.112	0.327	106.34	0.0000086	111.97
North Pipe Tuberculated.—Length, 1 615.70 Ft.																				
" 18th, A.M..	(XXII)	10.0	11.40	51	6.645	6.626	0.019	6.6339	51	4.915	4.883	0.032	4.8996	1.7343	0.0010734	42.882	3.412	104.15	0.0010717	104.23
" 18th, P.M..	(XXIII)	1.20	3.0	51	6.802	6.739	0.063	6.7700	51	4.953	4.919	0.034	4.9345	1.8355	0.0011360	44.105	3.510	104.13	0.0011343	104.21
" 19th, A.M..	(XXIV)	10.0	11.40	396	5.442	5.415	0.027	5.4254	211	4.554	4.516	0.038	4.5316	0.8938	0.0005532	31.034	2.470	105.00	0.0005515	105.16
" 19th, P.M..	(XXV)	1.20	3.0	397	5.409	5.399	0.010	5.4033	199	4.532	4.519	0.013	4.5249	0.8784	0.0005437	30.657	2.440	104.63	0.0005420	104.79
" 20th, A.M..	(XXVI)	10.0	11.40	201	5.956	5.953	0.003	5.9541	201	5.929	5.924	0.005	5.9265	0.0276	0.0000171	5.228	0.416	100.66	0.0000154	105.98
" 20th, P.M..	(XXVII)	1.20	3.0	201	5.954	5.940	0.014	5.9507	201	5.925	5.921	0.004	5.9225	0.0282	0.0000175	5.053	0.402	96.24	0.0000158	101.21
" 30th, A.M..	(XXVIII)	10.0	11.40	201	5.329	5.322	0.007	5.3258	201	5.150	5.129	0.021	5.1416	0.1842	0.0001140	14.269	1.135	106.34	0.0001123	107.13
" 30th, P.M..	(XXIX)	1.20	3.0	201	5.332	5.328	0.004	5.3239	201	5.151	5.139	0.012	5.1443	0.1856	0.0001149	14.300	1.138	106.18	0.0001132	106.96
North Pipe Clean.—Length, 1 615.70 Ft.																				
Nov. 30th, A.M..	(XXX)	10.0	11.40	51	6.112	6.081	0.031	6.0971	51	5.012	4.987	0.025	4.9991	1.0980	0.0006796	46.169	3.674	140.93	0.0006779	141.10
" 30th, P.M..	(XXXI)	1.20	3.0	197	6.106	6.088	0.018	6.0966	201	5.016	4.991	0.025	5.0035	1.0931	0.0006765	46.278	3.683	141.59	0.0006748	141.77
Dec. 1st, A.M..	(XXXII)	10.0	11.40	201	5.072	5.047	0.025	5.0588	199	4.543	4.524	0.019	4.5335	0.5253	0.0003251	31.068	2.472	137.11	0.0003234	137.46
" 1st, P.M..	(XXXIII)	1.20	3.0	201	5.056	5.042	0.014	5.0487	196	4.545	4.523	0.022	4.5348	0.5139	0.0003181	31.115	2.476	138.84	0.0003164	139.21
" 7th, A.M..	(XXXIV)	10.0	11.40	201	6.523	6.510	0.013	6.5177	198	6.411	6.393	0.018	6.4036	0.1141	0.0000706	13.989	1.113	132.47	0.0000689	134.07
" 7th, P.M..	(XXXV)	1.20	3.0	201	6.535	6.522	0.013	6.5288	198	6.416	6.403	0.013	6.4094	0.1194	0.0000739	14.177	1.128	131.24	0.0000722	132.75
" 8th, A.M..	(XXXVI)	10.0	11.40	201	6.014	6.009	0.005	6.0118	201	5.993	5.989	0.004	5.9905	0.0213	0.0000132	4.968	0.395	108.88	0.0000115	116.51
" 8th, P.M..	(XXXVII)	1.20	3.0	197	6.017	6.011	0.006	6.0135	201	5.996	5.990	0.006	5.9937	0.0198	0.0000123	4.998	0.398	113.62	0.0000106	122.26
" 13th, A.M..	(XXXVIII)	10.0	11.40	201	5.835	5.809	0.026	5.8200	201	4.907	4.874	0.033	4.8885	0.9315	0.0005765	42.551	3.386	141.02	0.0005748	141.22
" 13th, P.M..	(XXXIX)	1.20	3.0	201	5.833	5.799	0.034	5.8141	201	4.909	4.871	0.038	4.8889	0.9252	0.0005726	42.565	3.387	141.55	0.0005709	141.76
" 14th, A.M..	(XL)	10.0	11.40	201	6.182	6.169	0.013	6.1734	199	6.137	6.123	0.014	6.1273	0.0461	0.0000285	8.287	0.659	123.46	0.0000268	127.24
" 14th, P.M..	(XLI)	1.20	3.0	194	6.175	6.166	0.009	6.1711	201	6.131	6.121	0.010	6.1246	0.0465	0.0000288	8.247	0.656	122.33	0.0000271	126.04
" 15th, A.M..	(XLII)	10.0	11.40	201	6.097	6.085	0.012	6.0900	200	6.060	6.052	0.008	6.0549	0.0351	0.0000217	6.727	0.535	114.85	0.0000200	119.54
" 15th, P.M..	(XLIII)	1.20	3.0	196	6.096	6.085	0.011	6.0913	201	6.064	6.060	0.004	6.0619	0.0294	0.0000182	6.776	0.539	126.40	0.0000165	132.64
" 24th, A.M..	(XLIV)	10.0	11.40	188	6.002	5.932	0.070	5.9673	192	3.090	2.944	0.146	3.0106	2.9567	0.0018300	77.164	6.141	143.54	0.0018283	143.61
" 24th, P.M..	(XLV)	1.20	3.0	201	5.997	5.922	0.075	5.9604	196	3.089	2.912	0.177	3.0052	2.9552	0.0018291	76.949	6.123	143.18	0.0018274	143.25
1895.																				
Jan. 10th, A.M..	(XLVI)	10.0	11.40	187	5.953	5.930	0.023	5.9393	185	4.831	4.730	0.101	4.7786	1.1607	0.0007184	46.785	3.723	138.91	0.0007167	139.07
" 10th, P.M..	(XLVII)	1.20	3.0	186	5.960	5.930	0.030	5.9466	235	4.845	4.726	0.119	4.7834	1.1632	0.0007199	46.789	3.723	138.77	0.0007182	138.93
" 11th, A.M..	(XLVIII)	10.0	11.40	170	7.207	7.159	0.048	7.1835	186	5.217	5.139	0.078	5.1751	2.0084	0.0012431	62.493	4.973	141.05	0.0012414	141.14
" 16th, A.M..	(XLIX)	10.0	11.40	182	7.631	7.556	0.075	7.6012	191	3.477	3.439	0.038	3.4547	4.1465	0.0025664	90.498	7.202	142.16	0.0025647	142.21
" 16th, P.M..	(L)	1.20	3.0	182	7.746	7.680	0.066	7.7088	188	3.516	3.464	0.052	3.4902	4.2186	0.0026110	91.037	7.245	141.78	0.0026093	141.83
South Pipe Tuberculated.—Length, 1 615.70 Ft.																				
" 23d, A.M..	(LI)	10.0	11.40	186	6.015	5.990	0.025	6.0013	186	4.226	4.148	0.078	4.1742	1.8271	0.0011308	46.231	3.679	109.40	0.0011299	109.44
" 23d, P.M..	(LII)	1.20	3.0	180	6.037	6.010	0.027	6.0252	186	4.234	4.157	0.077	4.1847	1.8405	0.0011391	46.546	3.704	109.75	0.0011382	109.79
" 24th, A.M..	(LIII)	10.0	11.40	186	6.652	6.613	0.039	6.6323	178	3.368	3.225	0.143	3.2902	3.3421	0.0020685	62.579	4.980	109.49	0.0020676	109.51
" 24th, P.M..	(LIV)	1.20	3.0	185	6.717	6.689	0.028	6.7021	187	3.399	3.252	0.147	3.3017	3.4004	0.0021046	62.870	5.003	109.06	0.0021037	109.08
" 25th, A.M..	(LV)	10.0	11.40	170	6.873	6.844	0.029	6.8574	187	2.686	2.625	0.061	2.6378	4.2196	0.0026116	70.100	5.578	109.16	0.0026107	109.18
" 25th, P.M..	(LVI)	1.20	3.0	157	6.921	6.895	0.026	6.9098	187	2.662	2.634	0.028	2.6495	4.2603	0.0026368	70.253	5.591	108.87	0.0026359	108.89

TABLE No. 4.—TUBE PIEZOMETER OBSERVATIONS.

1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Date.	Number of experiment.	Time of beginning.	Time of ending.	West Tube Piezometer Readings.					East Tube Piezometer Readings.					Mean total fall in pipe. Feet.	Fall per foot of pipe. I_3. Feet.	Mean velocity of flow in pipe. From table 3, col. 17. v Feet per second.	Coefficient in $v = c_3\sqrt{RI_3}$. c_3.	Results from cols. 15 and 17 corrected for water levels.	
				Number of observations.	Highest. Feet.	Lowest. Feet.	Range. Feet.	Mean. Feet.	Number of observations.	Highest. Feet.	Lowest. Feet.	Range. Feet.	Mean. Feet.					I_4.	c_4.
South Pipe Tuberculated.—Length, 1 747.96 Ft.																			
1894. Sept. 4th, P.M..	1	1.20	1.40	11	6.639	6.631	0.008	6.6345	11	4.855	4.849	0.006	4.8508	1.7837	0.0010204	3.486	109.12		
	2	1.40	2.0	11	6.640	6.632	0.008	6.6357	11	4.850	4.845	0.005	4.8475	1.7882	0.0010230	3.493	109.20		
	3	2.0	2.20	11	6.643	6.635	0.008	6.6384	11	4.851	4.845	0.006	4.8493	1.7891	0.0010235	3.493	109.17		
	4	2.20	2.40	11	6.643	6.637	0.006	6.6420	11	4.850	4.848	0.002	4.8480	1.7940	0.0010263	3.494	109.06		
	5	2.40	3.0	11	6.645	6.638	0.007	6.6428	11	4.848	4.846	0.002	4.8470	1.7958	0.0010274	3.495	109.03		
	(I)	1.20	3.0	51	6.645	6.631	0.014	6.6387	51	4.855	4.845	0.010	4.8485	1.7902	0.0010242	3.492	109.12	0.0010205	109.32
1894. Sept. 5th, A.M..	(II)	10.0	11.40	51	5.398	5.383	0.015	5.3898	51	4.505	4.483	0.022	4.4931	0.8967	0.0005130	2.483	109.64	0.0005093	110.04
" 5th, P.M..	(III)	1.20	3.0	51	5.375	5.368	0.007	5.3710	51	4.491	4.486	0.005	4.4885	0.8825	0.0005049	2.466	109.75	0.0005012	110.16
" 6th, A.M	(IV)	10.0	11.40	51	5.351	5.345	0.006	5.3477	51	5.155	5.140	0.015	5.1464	0.2013	0.0001152	1.176	109.57	0.0001115	111.38
" 6th, P.M..	(V)	1.20	3.0	51	5.341	5.338	0.003	5.3394	51	5.150	5.140	0.010	5.1443	0.1951	0.0001116	1.164	110.19	0.0001079	112.07
" 7th, A.M..	(VI)	10.0	11.40	51	6.053	6.049	0 004	6.0514	51	6.023	6.016	0.007	6.0192	0.0322	0.0000184	0.404	94.07	0.0000147	105.30
" 7th, P.M..	(VII)	1.20	3.0	51	6.043	6.041	0.002	6.0418	51	6.016	6.013	0.003	6.0139	0.0279	0.0000160	0.395	98.94	0.0000123	112.97
" 11th, A.M..	(VIII)	10.0	11.40	85	6.109	6.085	0.026	6.0964	51	4.715	4.696	0.019	4.7035	1.3929	0.0007969	3.057	108.28	0.0007932	108.53
" 11th, P.M..	(IX)	1.20	3.0	51	6 072	6.053	0.019	6.0618	51	4.704	4.698	0.006	4.6995	1.3623	0.0007794	3.040	108.90	0.0007757	109 16
" 12th, A.M..	(X)	10.0	11.40	49	5.903	5.900	0.003	5.9017	51	5.425	5.408	0.017	5.4193	0.4824	0.0002760	1.810	108.98	0.0002723	109.72
" 12th, P.M..	(XI)	1.20	3.0	51	5.892	5.884	0.008	5.8880	51	5.425	5.405	0.020	5.4129	0.4751	0.0002718	1.793	108.76	0.0002681	109.51
" 13th, A.M..	(XII)	10.0	11.40	51	6.402	6.399	0.003	6.4016	51	6.285	6.277	0.008	6.2803	0.1213	0.0000694	0.905	108.61	0.0000657	111.64
" 13th, P.M..	(XIII)	1.20	3.0	51	6.398	6.395	0.003	6.3968	51	6 281	6.275	0.006	6.2776	0.1192	0.0000682	0.901	109.05	0.0000645	112.15
" 14th, A.M..	(XIV)	10.0	11.40	51	6.163	6.156	0.007	6.1591	51	6.106	6.098	0.008	6.1013	0.0578	0.0000331	0.605	105 27	0.0000294	111.74
" 14th, P.M..	(XV)	1.20	3.0	51	6.153	6.150	0.003	6.1523	51	6.097	6.094	0.003	6.0952	0.0571	0.0000327	0.595	104.12	0.0000290	110.61
Oct. 4th, A.M..	(XVI)	10.0	11.40	51	6.688	6.625	0.063	6.6579	51	4 852	4.828	0.024	4.8434	1.8145	0.0010381	3.472	107.76	0.0010344	107.95
" 4th, P.M..	(XVII)	1.20	3.0	51	6.770	6.728	0.042	6.7527	51	4.874	4.857	0.017	4.8654	1.8873	0.0010797	3.533	107.53	0.0010760	107.72
" 5th, A.M..	(XVIII)	10.0	11.40	51	5.422	5.395	0.027	5.4073	51	5.196	5.177	0.019	5.1851	0.2222	0.0001271	1.228	108.88	0.0001234	110.51

Oct. 5th, P.M..	(XIX)	1.20	3.0	51	5.383	5.375	0.008	5.3793	51	5.177	5.162	0.015	5.1684	0.2109	0.0001207	1.192	108.55	0.0001170	110.26
" 6th, A.M..	(XX)	10.0	11.40	51	6.024	6.020	0.004	6.0221	51	6.002	5.997	0.005	6.0001	0.0220	0.0000126	0.332	93.59	0.0000089	111.50
" 6th, P.M..	(XXI)	1.20	3.0	51	6.018	6.011	0.007	6.0141	51	6.012	5.992	0.020	5.9972	0.0169	0.0000097	0.327	105.24	0.0000060	134.15
North Pipe Tuberculated.—Length, 1 748.10 Ft.																			
" 18th, A.M..	(XXII)	10.0	11.40	51	6.755	6.731	0.024	6.7418	51	4.895	4.854	0.041	4.8804	1.8614	0.0010648	3.412	104.57	0.0010600	104.80
" 18th, P.M..	(XXIII)	1.20	3.0	50	6.913	6.843	0.070	6.8776	51	4.945	4.899	0.046	4.9179	1.9597	0.0011210	3.510	104.83	0.0011162	105.05
" 19th, A.M..	(XXIV)	10.0	11.40	51	5.493	5.469	0.024	5.4795	51	4.530	4.505	0.025	4.5200	0.9595	0.0005489	2.470	105.41	0.0005441	105.87
" 19th, P.M..	(XXV)	1.20	3.0	51	5.461	5.443	0.018	5.4510	51	4.515	4.499	0.016	4.5059	0.9451	0.0005406	2.440	104.92	0.0005358	105.38
" 20th, A.M..	(XXVI)	10.0	11.40	51	5.959	5.949	0.010	5.9528	51	5.923	5.913	0.010	5.9177	0.0351	0.0000201	0.416	92.84	0.0000153	106.25
" 20th, P.M..	(XXVII)	1.20	3.0	51	5.943	5.939	0.004	5.9410	51	5.910	5.909	0.001	5.9092	0.0318	0.0000182	0.402	94.27	0.0000134	109.66
" 30th, A.M..	(XXVIII)	10.0	11.40	51	5.348	5.343	0.005	5.3447	50	5.149	5.133	0.016	5.1405	0.2042	0.0001168	1.135	105.06	0.0001120	107.26
" 30th, P.M..	(XXIX)	1.20	3.0	51	5.353	5.351	0.002	5.3519	51	5.152	5.135	0.017	5.1446	0.2073	0.0001186	1.138	104.50	0.0001138	106.66
North Pipe Clean.—Length, 1 748.10 Ft.																			
Nov. 30th, A.M..	(XXX)	10.0	11.40	46	6.189	6.175	0.014	6.1797	51	5.001	4.981	0.020	4.9906	1.1891	0.0006802	3.674	140.87	0.0006754	141.36
" 30th, P.M..	(XXXI)	1.20	3.0	46	6.186	6.183	0.003	6.1842	51	5.002	4.983	0.019	4.9920	1.1922	0.0006820	3.683	141.02	0.0006772	141.51
Dec. 1st, A.M..	(XXXII)	10.0	11.40	46	5.095	5.089	0.006	5.0915	36	4.531	4.514	0.017	4.5239	0.5676	0.0003247	2.472	137.20	0.0003199	138.21
" 1st, P.M..	(XXXIII)	1.20	3.0	47	5.090	5.083	0.007	5.0858	51	4.533	4.520	0.013	4.5257	0.5601	0.0003204	2.476	138.33	0.0003156	139.37
" 7th, A.M..	(XXXIV)	10.0	11.40	46	6.538	6.525	0.013	6.5312	51	6.408	6.391	0.017	6.4004	0.1308	0.0000748	1.113	128.69	0.0000700	132.98
" 7th, P.M..	(XXXV)	1.20	3.0	46	6.549	6.536	0.013	6.5442	51	6.414	6.401	0.013	6.4086	0.1356	0.0000776	1.128	128.10	0.0000728	132.21
" 8th, A.M..	(XXXVI)	10.0	11.40	46	6.018	6.010	0.008	6.0133	51	5.995	5.989	0.006	5.9917	0.0216	0.0000124	0.395	112.46	0.0000076	143.32
" 8th, P.M..	(XXXVII)	1.20	3.0	49	6.024	6.018	0.006	6.0220	51	5.997	5.992	0.005	5.9941	0.0279	0.0000160	0.398	99.56	0.0000112	118.78
" 13th, A.M..	(XXXVIII)	10.0	11.40	85	5.905	5.878	0.027	5.8929	51	4.894	4.865	0.029	4.8783	1.0146	0.0005804	3.386	140.55	0.0005756	141.13
" 13th, P.M..	(XXXIX)	1.20	3.0	97	5.908	5.873	0.035	5.8912	51	4.837	4.862	0.025	4.8764	1.0148	0.0005805	3.387	140.58	0.0005757	141.16
" 14th, A.M..	(XL)	10.0	11.40	48	6.188	6.178	0.010	6.1823	51	6.132	6.124	0.008	6.1281	0.0542	0.0000310	0.659	118.43	0.0000262	128.69
" 14th, P.M..	(XLI)	1.20	3.0	48	6.186	6.179	0.007	6.1819	50	6.129	6.117	0.012	6.1232	0.0587	0.0000336	0.656	113.25	0.0000288	122.22
" 15th, A.M..	(XLII)	10.0	11.40	47	6.097	6.089	0.008	6.0925	51	6.064	6.052	0.012	6.0587	0.0338	0.0000193	0.535	121.74	0.0000145	140.16
" 15th, P.M..	(XLIII)	1.20	3.0	47	6.102	6.096	0.006	6.0982	51	6.061	6.054	0.007	6.0568	0.0414	0.0000237	0.539	110.80	0.0000189	123.92
" 24th, A.M..	(XLIV)	10.0	11.40	93	6.211	6.175	0.036	6.1943	46	2.992	2.952	0.040	2.9638	3.2305	0.0018480	6.141	142.84	0.0018432	143.02
" 24th, P.M..	(XLV)	1.20	3.0	49	6.183	6.163	0.020	6.1733	46	3.000	2.953	0.047	2.9692	3.2041	0.0018329	6.123	143.03	0.0018281	143.22
1895.																			
Jan. 10th, A.M..	(XLVI)	10.0	11.40	46	6.030	6.021	0.009	6.0264	46	4.832	4.720	0.112	4.7773	1.2491	0.0007145	3.723	139.28	0.0007097	139.75
" 10th, P.M..	(XLVII)	1.20	3.0	46	6.051	6.033	0.018	6.0426	46	4.812	4.707	0.105	4.7654	1.2772	0.0007306	3.723	137.75	0.0007258	138.20
" 11th, A.M..	(XLVIII)	10.0	11.40	46	7.345	7.311	0.034	7.3282	46	5.193	5.112	0.081	5.1513	2.1769	0.0012453	4.973	140.92	0.0012405	141.19
" 16th, A.M..	(XLIX)	10.0	11.40	46	7.963	7.863	0.100	7.9107	46	3.419	3.387	0.032	3.4056	4.5051	0.0025771	7.202	141.86	0.0025723	141.99
" 16th, P.M..	(L)	1.20	3.0	46	8.061	7.984	0.077	8.0204	47	3.512	3.358	0.154	3.4360	4.5844	0.0026225	7.245	141.47	0.0026177	141.60
South Pipe Tuberculated.—Length, 1 747.96 Ft.																			
Jan. 23d, A.M..	(LI)	10.0	11.40	51	6.135	6.113	0.022	6.1249	51	4.180	4.122	0.058	4.1536	1.9713	0.0011278	3.679	109.55	0.0011241	109.73
" 23d, P.M..	(LII)	1.20	3.0	51	6.163	6.144	0.019	6.1524	51	4.232	4.132	0.100	4.1735	1.9789	0.0011321	3.704	110.09	0.0011284	110.27
" 24th, A.M..	(LIII)	10.0	11.40	51	6.869	6.835	0.034	6.8538	51	3.271	3.232	0.039	3.2542	3.5996	0.0020593	4.980	109.74	0.0020556	109.84
" 24th, P.M..	(LIV)	1.20	3.0	51	6.935	6.916	0.019	6.9275	51	3.360	3.202	0.158	3.2765	3.6510	0.0020887	5.003	109.47	0.0020850	109.57
" 25th, A.M..	(LV)	10.0	11.40	51	7.150	7.128	0.022	7.1362	51	2.721	2.565	0.156	2.6047	4.5315	0.0025925	5.578	109.56	0.0025888	109.64
" 25th, P.M..	(LVI)	1.20	3.0	51	7.204	7.188	0.016	7.1961	51	2.623	2.601	0.022	2.6106	4.5855	0.0026233	5.591	109.15	0.0026196	109.23

TABLE No. 5.—COMPARISON BETWEEN SIPHON AND TERMINAL CHAMBER WEIRS.

Using Bazin's values of m in the formula $Q = m\,L\,H\sqrt{2\,g\,H}$; $g = 32.17$.

OBSERVATIONS AT SIPHON WEIR.

1	2	3	4		5	6	7	8	9	10
Date.	Number of experiment.	Temperature of water. Fahrenheit.	Time of beginning.	Time of ending.	Number of observations.	Mean height of water on weir. H. Feet.	Mean length of weir. L. Feet.	Coefficient from table. m.	Quantity in cubic feet per second. Q.	Ratio of quantity at siphon weir to quantity at terminal weirs.
1894.										
November 13th...........	1	38.8°	9.00 A.M.	12.20 P.M.	41	1.8897	4.9693	0.4429	45.860	0.9915
" 15th...........	2	38.7°	9.00 A.M.	1.40 P.M.	57	1.8748	4.9693	0.4427	45.298	0.9926
" 16th...........	3	39.0°	9.00 A.M.	1.40 P.M.	57	1.8790	4.9693	0.4427	45.450	0.9848
" 30th...........	4	35.5°	10.00 A.M.	11.40 A.M.	51	1.8979	4.9693	0.4430	46.169	0.9919
December 1st...........	5	35.5°	10.00 A.M.	11.40 A.M.	51	1.4699	4.9700	0.4373	31.068	0.9884
" 13th...........	6	....	10.00 A.M.	11.20 A.M.	41	1.8021	4.9694	0.4417	42.593	0.9924
" 21st...........	7	....	9.00 A.M.	12.20 P.M.	81	1.9392	4.9692	0.4435	47.737	0.9783
	Mean.....	....	....	....	....	....	....	....	....	0.9886

Observations at Terminal Weirs.

1	2	3	4		5	6	7	8	9	10	11	12	13	14	15	16
					East Weir.					West Weir.						
Date.	Number of experiment.	Temperature of water. Fahrenheit.	Time of beginning.	Time of ending.	Number of observations.	Mean height of water on weir. H. Feet.	Mean length of weir. L. Feet.	Coefficient from table. m.	Quantity in cubic feet per second. Q.	Number of observations.	Mean height of water on weir. H. Feet.	Mean length of weir. L. Feet.	Coefficient from table. m.	Quantity in cubic feet per second. Q.	Total quantity in cubic feet per second.	Total quantity less 0.558 cu. ft. per second leakage. Cubic feet per second.
1894.			P M	P.M.												
November 13th......	1	....	1.40	4.58	50	1.0720	6.3259	0.4284	24.127	50	1.0848	5.8411	0.4285	22.684	46.811	46.253
" 15th......	2	39.1°	2.20	7.00	141	1.6403	6.3238	0.4335	46.195	....	......	......	......	......	46.195	45.637
" 16th......	3	39.1°	2.20	7.00	....	......	......	......	......	140	1.7399	5.8396	0.4345	46.709	46.709	46.151
" 30th......	4	36.1°	3.20	5.00	51	1.6613	6.3237	0.4337	47.106	....	......	......	......	......	47.106	46.548
December 1st	5	36.1°	4.30	6.10	....	......	......	......	......	51	1.3594	5.8408	0.4308	31.990	31.990	31.432
" 13th......	6	36.6°	3.00	4.20	40	1.0206	6.3261	0.4280	22.393	41	1.0339	5.8411	0.4281	21.086	43.479	42.921
" 21st......	7	37.1°	1.40	5.00	100	1.1089	6.3258	0.4287	25.401	101	1.1244	5.8410	0.4288	23.953	49.354	48.796

TABLE No. 6.—Water Level Observations.

Piezometer Gauges.

1	2	3		4	5	6	7	8	
Date.	Number of experiment.	Time of beginning.	Time of ending.	West Piezometer. Number of observations.	West Piezometer. Mean reading. Feet.	East Piezometer. Number of observations.	East Piezometer. Mean reading. Feet.	Differences. E. piezometer reading minus, W. piezometer reading feet.	
North Pipe.									
1894.									
September 7th, P. M.	1	1.20	3.00	46	4.3046	45	4.2909	−0.0137	
" 11th, P. M.	2	1.20	3.00	50	5.3540	50	5.3421	−0.0119	
" 12th, A. M.	3	10.00	11.40	50	4.2514	50	4.2528	0.0014	
" 12th, P. M.	4	1.20	3.00	50	5.4396	50	5.4335	−0.0061	
" 13th, A. M.	5	10.00	11.40	50	3.9089	50	3.9105	0.0016	
" 13th, P. M.	6	1.20	3.00	50	3.9096	50	3.9060	−0.0036	
" 14th, A. M.	7	10.00	11.40	50	3.8730	50	3.8742	0.0012	
" 14th, P. M.	8	1.20	3.00	50	3.8747	50	3.8735	−0.0012	
October 4th, A. M.	9	10.00	11.40	50	3.9531	50	3.9528	−0.0003	
" 4th, P. M.	10	1.20	3·00	50	4.0440	50	4.0408	−0.0032	
" 5th, A. M.	11	10.00	11.40	50	4.2414	50	4.2368	−0.0046	
" 5th, P. M.	12	1.20	3.00	50	4.2392	50	4.2345	−0.0047	
" 6th, A. M.	13	10.00	11.40	50	4.2508	50	4.2559	0.0051	
" 6th, P. M.	14	1.20	3.00	50	4.2481	50	4.2503	0.0022	
	Mean							−0.0027	±0.00097
	Vernier correction							+0.0008	
	Correction for zero of scale							= −0.0019	

SOUTH PIPE.

1894.									
October	18th, P. M.	15	1.20	3.00	50*	....	50*	....	....
"	19th, A. M.	16	10.00	11.40	208	5.0639	195	5.0658	0.0019
"	19th, P. M.	17	1.20	3.00	200	5.0425	200	5.0428	0.0003
"	20th, A. M.	18	10.00	11.40	187	4.8910	194	4.8917	0.0007
"	20th, P. M.	19	1.20	3.00	177	4.8637	204	4.8610	—0.0027
"	30th, A. M.	20	10.00	11.40	201	3.7612	201	3.7608	—0.0004
"	30th, P. M.	21	1 20	3.00	201	3.7598	201	3.7596	—0.0002
November	30th, A. M.	22	10.00	11.40	50*	....	50*	....	....
"	30th, P. M.	23	1.20	3.00	158	4.2604	201	4.2633	0.0029
December	1st, A. M.	24	10.00	11.40	188	4.0946	199	4.0908	—0.0038
"	1st, P M.	25	1.20	3.00	197	4.0921	197	4.0899	—0.0022
"	7th, A. M.	26	10.00	11.40	201	5.9003	201	5.9000	—0.0004
"	7th, P. M.	27	1.20	3.00	201	5.7739	201	5.7704	—0.0035
"	8th, A. M.	28	10.00	11.40	201	5.4098	201	5.4052	—0.0046
"	8th, P. M.	29	1.20	3.00	197	5.3845	201	5.3818	—0.0027
"	13th, A. M.	30	10.00	11.40	201	6 4096	201	6.4067	—0.0029
"	13th, P. M.	31	1.20	3.00	201	6.3653	201	6.3638	—0.0015
"	14th, A M.	32	10.00	11.40	201	5.8852	191	5.8831	—0.0021
"	14th, P. M	33	1.20	3.00	198	5.8622	201	5 8601	—0.0021
"	15th, A. M.	34	10.00	11.40	201	5.3347	198	5.3302	—0.0015
"	15th, P. M.	35	1.20	3.00	197	5.3223	198	5.3218	—0.0005

Mean .... —0.0015 ±0.00032
Vernier correction .... —0.0005

Correction for zero of scale .... —0.0020

* Observations not used in obtaining mean, because they were taken at two-minute intervals instead of 30 second intervals, and are therefore of less weight than the others.

TABLE No. 7.—Water Level Observations.

Tube Piezometer Gauges.

1	2	3		4	5	6	7	8	
				West Tube Piezometer.		East Tube Piezometer.			
Date.	Number of experiment.	Time of beginning.	Time of ending.	Number of observations.	Mean reading. Feet.	Number of observations.	Mean reading. Feet.	Differences. E. piezometer reading minus. W. piezometer reading feet.	
North Pipe.									
1894.									
September 7th, P.M.	1	1.20	3.00	50	4.2924	50	4.2865	—0.0059	
" 11th, P.M.	2	1.20	3.00	50	5.3512	50	5.3389	—0.0123	
" 12th, A.M.	3	10.00	11.40	49	4 2626	50	4.2536	—0.0090	
" 12th, P.M.	4	1.20	3.00	50	5.4413	50	5.4295	—0 0118	
" 13th, A.M.	5	10.00	11.40	50	3.9197	50	3.9080	—0.0117	
" 13th, P.M.	6	1.20	3.00	50	3.9119	50	3.9010	—0.0109	
" 14th, A.M.	7	10.00	11.40	49	3.8847	50	3.8761	—0.0086	
" 14th, P.M.	8	1.20	3.00	47	3.8834	50	3.8756	—0 0078	
October 4th, A.M.	9	10.00	11.40	50	3.9557	50	3.9466	—0.0091	
" 4th, P.M.	10	1.20	3.00	50	4.0442	49	4.0376	—0.0066	
" 5th, A.M.	11	10.00	11.40	50	4.2382	50	4.2328	—0.0054	
" 5th, P.M.	12	1.20	3 00	50	4.2333	50	4.2253	—0.0080	
" 6th, A.M.	13	10.00	11.40	50	4.2590	50	4.2517	—0.0073	
" 6th, P.M.	14	1 20	3.00	50	4.2548	50	4.2534	—0.0014	
	Mean	....	....	....	....	....	....	—0.0083	±0.00053

SOUTH PIPE.

1894.									
October 18th, P.M.	15	1.20	3.00	51	5.2234	50	5·2128	—0.0106	
" 19th, A.M.	16	10.00	11.40	50	5.0639	50	5.0585	—0.0054	
" 19th, P.M.	17	1.20	3.00	50	5.0375	50	5.0312	—0.0063	
" 20th, A.M.	18	10.00	11.40	50	4.8869	50	4.8796	—0.0073	
" 20th, P.M	19	1.20	3.00	50	4.8516	50	4.8452	—0.0064	
" 30th, A.M.	20	10.00	11.40	50	3.7623	50	3.7592	—0.0031	
" 30th, P.M.	21	1.20	3.00	50	3.7633	50	3.7569	—0.0064	
November 30th, A.M.	22	10.00	11.40	45	4.3253	50	4.3151	—0.0102	
" 30th, P.M.	23	1.20	3.00	45	4.2652	50	4.2555	—0.0097	
December 1st, A.M.	24	10.00	11.40	45	4.0880	50	4.0852	—0.0028	
" 1st, P.M.	25	1.20	3.00	45	4.0848	50	4.0826	—0.0022	
" 7th, A.M.	26	10.00	11.40	45	5.9025	50	5.8938	—0.0087	
" 7th, P.M.	27	1.20	3.00	45	5.7721	50	5.7650	—0.0071	
" 8th, A.M.	28	10.00	11.40	45	5.4064	50	5.4011	—0.0053	
" 8th, P.M.	29	1.20	3.00	45	5.3861	50	5.3765	—0.0096	
" 13th, A.M.	30	10.00	11.40	90	6.4111	50	6.4082	—0.0029	
" 13th, P.M.	31	1.20	3.00	95	6.3764	50	6.3627	—0.0137	
" 14th, A.M.	32	10.00	11.40	47	5.8824	50	5.8789	—0.0035	
" 14th, P.M.	33	1.20	3.00	47	5.8632	49	5.8543	—0.0089	
" 15th, A.M.	34	10.00	11.40	50	5.3299	50	5.3296	—0.0003	
" 15th, P.M.	35	1.20	3.00	46	5.3214	50	5.3148	—0.0066	
	Mean	....	....	....	....	....	....	—0.0065	±0.00049

DISCUSSION.

Mr. Gould.

E. Sherman Gould, M. Am. Soc. C. E.—Such elaborate and painstaking experiments as those conducted and described by the author are of the highest scientific value. In the present case, however, one circumstance seems to impair the usefulness of the results, namely, that the line experimented on, being only about 420 diameters in length, cannot be classed fairly as a long pipe. It is to be regretted, also, that the difference of level of the water surfaces in the two gatehouses was not recorded as well as that of the piezometric heights. This would have been a valuable addition to the data.

These experiments show unusually large volumes of water passing through the cleaned pipes at the higher velocities. The most natural explanation of this lies in the fact already stated, that the pipe is not really a long pipe, and that, therefore, with a very clean surface and relatively steep hydraulic gradient, the interior resistances did not have a chance to exert their full influence. It is to be feared that dangerous generalizations may arise from these experiments, and the formulas derived from them may be used incautiously in cases to which they do not apply.

As regards the choice of a safe, practical formula for the flow of water through long pipes, it may be laid down as a fundamental principle, that it should conform to the ordinary requirements of all practical engineering formulas.

The only test of the merit of an engineering formula is whether, in a vast majority of practical cases, it gives results below rather than above those commonly realized. If it does this, it is a good formula, no matter how it was derived, whether by elaborate experiment or mere guess. Moreover, a safe engineering formula cannot always be derived even from experiment, because the experiment is necessarily conducted under circumstances which do not or may not exist in practice. An elaborate experiment is useful to establish a law of nature, such as universal attraction or the mechanical equivalent of heat, but it cannot establish a practical engineering formula. That must be founded upon the general behavior of the working apparatus as commonly constructed. In this case it is the apparatus about which information is wanted and not the law.

As a safe, simple and practical formula for the flow of water through long pipes, it is believed that no other is so good as that of Darcy, and in making this assertion, the perfection of the experiments upon which it is founded is waived, and the statement based entirely upon the concordance of its results with those realized in practice. This formula is thus expressed:

$$V = \sqrt{D\,H \div C\,L} \qquad (1)$$

Whence,

$$Q = A\sqrt{D\,H \div C\,L} \qquad (2)$$

In these formulas, V is the velocity in feet per second, D is the diameter of the pipe in feet, H is the total head, L is the length of pipe, C is a numerical coefficient, Q is the discharge in cubic feet per second, and A is the area of pipe in square feet. Mr. Gould.

The coefficient C varies for clean pipes, from 0.00033 for a pipe 1 ft. in diameter to 0.00031 for one of 4 ft. For rough pipes the above values become 0.00066 and 0.00062 respectively.

Formula (2) may be written thus:

$$Q = \sqrt{0.617\ D^5\ H \div C\ L}$$

If C in this formula is assumed to be 0.0003085 for smooth and 0.000617 for rough pipes, and if L is taken as 1 000, and h as the fall or head per 1 000, there results for smooth pipes:

$$Q = \sqrt{2\ h\ D^5} \qquad (3)$$

$$D = \sqrt[5]{Q^2 \div 2\ h} \qquad (4)$$

and

$$Q = \sqrt{D^5\ h} \qquad (5)$$

$$D = \sqrt[5]{Q^2 \div h} \qquad (6)$$

for rough pipes. Also

$$V = \sqrt{3.24\ D\ h} \qquad (7)$$

for smooth pipes, and

$$V = \sqrt{1.62\ D\ h} \qquad (8)$$

for rough pipes.

It will be seen that the extreme variation between a smooth and a rough pipe is here assumed as $\sqrt{2}$, or, say, 40% greater in the former than in the latter. Or to state it in another manner, the discharge of the rough pipe is 0.707, say 70%, of that of the smooth pipe.

To submit these formulas to the only true test, that of practical results, they may be compared with the examples given by Edmund B. Weston, M. Am. Soc. C. E., in his valuable paper, "The Results of Investigations Relative to Formulas for the Flow of Water in Pipes." *

The examples taken are for diameters of 12, 16, 20, 30, 36 and 48 ins. The author's observed results have been added for comparison.

In the table on page 278, the first column gives the name of the experimeter; the second, the nature of the pipe; the third, the diameter in inches; the fourth, the fall per 1 000; the fifth, the observed velocity; and the sixth and seventh, the velocities according to Darcy's simplified formulas for smooth pipes (7) and rough pipes (8), respectively. These two formulas are interchangeable by the use of the coefficient 1.41 or 0.707, applied respectively to the formula for rough or smooth pipes.

It will be perceived that in all the range of practical examples taken from Mr. Weston's paper, the observed velocities lie between the extremes represented by formulas (7) and (8).

* See *Transactions*, Vol. xxii, p. 1.

Mr. Gould.

Authority.	Character of pipe.	Diameter, inches.	Fall per 1 000.	Observed velocity, feet per second.	$V = \sqrt{3.24\,Dh}$	$V = \sqrt{1.62\,Dh}$
Simpson	Cast iron, less than seven years' service	12	0.77	1.45	1.58	1.12
"	Cast iron, less than seven years' service	12	7.70	4.35	5.00	3.53
"	Cast iron, less than four years' service	12	6.97	4.11	4.75	3.36
Bonn Water-Works	New cast iron, asphalted	12+	1.20	1.56	1.97	1.39
"	"	12	3.66	3.10	3.44	2.43
Edinburgh Water-Works	Cast iron, eight or nine years' service	16	8.92	5.25	6.20	4.38
"	Cast iron, eight or nine years' service	16	48.23	14.51	14.40	10.18
Brush	Cast iron, tarred, five years' service	20	0.729	2.00	1.98	1.40
"	Cast iron, tarred, five years' service	20	1.49	2.76	2.83	2.00
"	Cast iron, tarred, five years' service	20	1.797	3.00	3.10	2.19
Simpson	Cast iron, two or three years' service	30	0.462	1.77	1.93	1.36
Greene	Cast iron, heavily tuberculated	36	1.80	3	4.16	2.95
Fitzgerald	South pipe, tuberculated	48	1.02	3.486	3.64	2.57
"	"	48	2.62	5.591	5.83	4.12
"	North pipe, tuberculated	48	0.0175	0.402	0.597	0.422
"	"	48	1.136	3.51	3.84	2.71
"	North pipe, clean	48	1.83	6.141	4.87	3.44
"	"	48	2.62	7.245	5.83	4.12
"	"	48	0.5765	3.3[illegible]6	2.73	1.93
"	"	48	0.0217	0.535	0.531	0.375
"	"	48	0.0123	0.398	0.399	0.282
					$V = R\sqrt{\frac{100\,h}{6.6\,R + 0.46}}$	
Clark	Brick tunnel	90	0.501	3.77	3.70	
"	"	90	0.582	3.93	3.99	

On the other hand, a marked difference is observable in the case of the author's cleaned pipes at the higher velocities, which greatly exceed the velocities given by formula (7), with which, however, they nearly agree for very low velocities of a few inches per second. The velocities for the tuberculated pipes fall between those given by formulas (7) and (8), as might be expected.

Setting aside the very low velocities, due to falls of less than 2 ins. per mile, which are of little practical interest, the fact remains that out of a large body of actual measurements the author's smooth pipes alone give results differing widely, in excess, from those given by Darcy's formula for similar pipes. Assuming the data in all cases to be correct, it seems that the most reasonable explanation is that already

suggested, namely, that the line was not sufficiently long for the full development of the resistances of the interior surface. The only other rational explanation would be an abnormal degree of smoothness of the surface, and either circumstance would annul the value of the experiments as practical guides. Mr. Gould.

In the case of the 90-in. brick tunnel, the observed velocity agrees admirably with that given by Darcy's formula for such conduits. This formula is conveniently rendered—

$$V = R\sqrt{\frac{100\,h}{6.6\,R + 0.46}} \qquad (9)$$

in which R is the mean hydraulic radius.

This last formula (9), which seems to be justified by other observations also, gives higher velocities than (7). Indeed, it seems reasonable that a brick-lined conduit, which is always laid to a true descending grade, with few bends and with a uniform interior surface, should give a higher rate of velocity than an iron pipe line, as generally laid.

The preceding table includes no diameters below 12 ins., because from and even at that diameter the coefficient C begins to increase so rapidly that the simplified formula would give too high comparative velocities. For smaller diameters formula (1) should be used, with the proper value for C, as established by Darcy. Mr. Weston's observations on a 6-in. pipe, given in his paper already referred to, justify the use of the simplified formula for pipes of this diameter also. In the absence of further observations, however, it would be best to use it for small diameters as an approximation only.

In view of the above facts, it would appear that Darcy's formula for rough pipes in its simplified form, given in equation (6), furnishes a safe rule to calculate diameters of cast-iron pipes from 12 to 48 ins., and that no formula giving smaller diameters should be trusted for a permanent water supply. It fulfils the essential condition of all working engineering formulas, that of containing a reasonable, but not extravagant, factor of safety.

CORRESPONDENCE.

Mr. Hering.

RUDOLPH HERING, M. Am. Soc. C. E.—No contribution of results obtained by actual experiment in the domain of hydraulic engineering can be more welcome than one referring to the discharging capacity of pipes under different conditions, on account of the money value which is often represented by them. There still seems to be a lack of full appreciation of the inductions that have been drawn from the few but well-authenticated gaugings which have been made, and therefore more evidence is needed to increase confidence in them. The author has rendered a good service to the profession in publishing a detailed account of his late experiments. They were evidently made with much care, and the results obtained are correspondingly accurate and valuable.

It is the writer's purpose to say a few words regarding the latter part of the paper, which is devoted to an expression of the results by formulas. Such algebraic aids are often of great value to a practical engineer, but sometimes they are the reverse, and, unless thoroughly understood, are liable, under the cloak of apparent exactness, to misrepresent facts and cause failures.

The author has made the simple Chezy formula the basis of his study, to which the writer desires to give a strong endorsement, not only because of its simplicity, but also because of its rational construction and practical usefulness. Unfortunately the less simple Weisbach and other "$2gh$" formulas are still occasionally used with apparent preference, probably because their theoretical origin is indicated a little more clearly to the eye, but to the practical man they are often unnecessarily clumsy and perhaps occasionally misleading.

The Chezy, or more properly the Brahms, formula is: Mean velocity $= c\sqrt{rs}$, in which r is the mean radius, s is the sine of slope, and the coefficient c, as originally supposed, was a constant, and was ascertained by experiment. For rough results, amply sufficient for many cases, this expression has been used for over a century, Brahms having first suggested it in 1753. With the development of hydraulics and the demand for greater precision, the so-called coefficient c was found to require modification when applied under different conditions. In other words, it was found by more extensive experience not to be a constant, but a variable, quantity.

Through the classic series of experiments conducted by Darcy and Bazin in France, it was found that the value of the coefficient varied greatly with the character or roughness of the wetted perimeter and also somewhat with the mean radius of the section. Humphreys and Abbot, in their experiments on the flow of the Mississippi River, found that the coefficient c varied with the hydraulic slope. Mr. Ganguillet,

city engineer of Berne, Switzerland, and a capable mathematician, suggested an algebraic expression for the coefficient c which would embody these three variations, and, together with Mr. Kutter, his assistant, developed what is now known as the Kutter formula. This formula, if applied to the experiments of Darcy and Bazin, is found not only to represent them well, but, on the average, actually better than Darcy's own formula. For ascertaining the flow of water in channels of regular section a new and more accurate expression was therefore given for the original coefficient c. Its variation with the mean radius and with the slope was given a mathematical form, because these quantities could be suitably expressed, and a new constant, the coefficient n, was introduced, which was intended to represent a certain definite degree of roughness of the wetted perimeter. Mr. Hering.

A much greater refinement was thus obtained, and the formula could be applied with greater confidence as regards the result. At first the authors of the Kutter formula divided all possible cases into classes or categories (as did Darcy and Bazin), and suggested six different values for the coefficient of roughness n, beginning with smooth cement or planed boards and ending with streams, the beds of which were covered with detritus and aquatic plants. Later these six classes were given up. The advantages of this new formula were grasped quickly by the engineering profession, and it gradually supplanted the old formulas for general use.

In recent years, however, through the further development of engineering science, the demand for greater refinements, for greater economy in getting better results with less expenditure of money, has put the Kutter formula in a similar position to that occupied by the Chezy formula thirty years ago. The coefficient n, which was first considered to be a constant quantity, and which roughly can be properly considered as such, is also found to vary, though between much smaller limits than the original coefficient c.

To illustrate this statement by the simile of a decimal fraction, suppose the Chezy formula gave results that could safely be expressed by units only, the greater refinement of the Kutter formula gave results which could be safely expressed in tenths of a unit. At the present time there seems to be need of a formula which will give safe results in hundredths of a unit. Gaugings are being made with greater precision. It is more necessary to-day that water courses and pipe lines should give the greatest discharges with the least possible outlay of money. Works built in recent years on the assumption, continuing to use the above simile, that accuracy up to tenths of a unit was sufficient, have, in more than one case, disastrously affected invested capital.

An important question to-day is how further improvements can be made in more accurately forecasting the mean flow of water in projected channels. By some radically new formula? The writer thinks

Mr. Hering. not. It seems there are already too many, and thereby have caused some little confusion rather than elucidation on the subject. To the writer's mind, the proper course to pursue appears to be the following: Starting with the old and simple Chezy formula as a foundation, its coefficient c may be considered a constant quantity for rough approximations, perhaps distinguishing between pipes, artificial channels and rivers. For closer approximations the Kutter formula may be used, which expresses mathematically some of the variations of this coefficient, and introduces a new coefficient n, which is readily ascertained in practice, because it represents mainly the degree of roughness of perimeter and can be interpreted by gaugings made in similar channels. For still closer approximation it is necessary to consider the variations of this coefficient of roughness in one and the same channel, with its slope and perhaps also with its size and shape. Attention should be paid to these variations when safer and more precise results are desired, rather than to attempts to find a radically new formula.

Realizing such a necessity in the future, the writer endeavored about ten years ago to plot curves from actual gaugings, in order to ascertain the nature of the variation of this coefficient of roughness n. Sufficient information was obtained to indicate the *rationale* and practicability of such a course. To facilitate application in practice the writer compiled a very large collection of gaugings* from the case of pipes to that of the largest rivers, and arranged them with the special purpose of showing the variation of Kutter's coefficient n with the variation of the slope in one and the same channel. By giving some attention to this variation, as indicated by known and carefully made gaugings, an engineer will be enabled to forecast the discharge of a channel much more safely, and by the constantly increasing stock of gaugings, including cases of every characteristic kind of surface, he will be able to get closer and closer to the truth, and thus better fulfil the increasing demands for accuracy and safety on the part of invested capital.

It is quite possible that the accumulation of gaugings, as they enabled Ganguillet and Kutter to devise a formula for the variation of the Chezy constant, will, through the greater number of more accurate gaugings since made available, enable some one to devise a formula for the variation of the Kutter constant. Until then, the available gaugings themselves must be used and interpreted by the engineer in applying them to each new case.

It has recently been stated by a member of this Society that it would not be possible to determine reliable, variable coefficients of roughness to answer for all localities, because some iron pipes corrode much

* Embodied in the appendix to Ganguillet and Kutter's work on "The Flow of Water," translated by Rudolph Hering and John C. Trautwine, Jr.

faster than others and consequently the degree of roughness of the interior of an iron pipe in one locality, after a few years of service, might be quite different from what it would be in another locality, where for instance the water had a different chemical composition. Mr. Hering.

This statement is one of those which are apt to cause confusion of ideas. No formula can ever be devised nor can any rule be determined whereby the flow of water in pipes can be ascertained, when such a formula or rule must depend upon a gradual and complex change of conditions, such as subsequent corrosion, a subsequent deposit of scale or sediment, attachment of a slimy coating or a vegetable growth. The probable future extent of these contingencies must be determined by a mental and not by an algebraic process, and the skilful engineer will decide for what kind or degree of such contingencies he thinks it proper to provide in his special case, and select the coefficients in accordance with his decision. Judgment will be very materially aided if the laws according to which the coefficients are found to vary have been ascertained and recognized. Instead of considering only two or three so-called constants, each one applying to a general class of conduits, and each one embracing a great variety of conditions, the engineer will be able to draw safer conclusions if he has a continuously increasing scale of coefficients before him, along which scale he finds those coefficients which represent actual gaugings for definite conditions, and between which lies the coefficient that must apply to his new case. By means of his judgment, then, weighing the differences between the conditions of his new case and those for which actual gaugings exist, he can locate a value along that scale for the coefficient which applies most nearly to his new case.

It is unfortunate that the author gives also three entirely new formulas of the exponential class to fit his three series of experiments, without a special warning, which he perhaps thought was unnecessary, that they should not be applied to other cases. Such a possibility should not always be excluded, because cases are occasionally found where such formulas have been misapplied. The exponential class offers easy adaptations for any short series of experiments, and thereby gives a semblance of accuracy to the formula and apparently justifies confidence, but when applied to other cases it is sometimes liable to hit far off the mark. It is much safer for practical purposes to use the old simple Chezy instead of the exponential form, and, according to the degree of accuracy desired or obtainable, vary the coefficient c according to the Kutter formula, and for finer work to vary also the coefficient n, in accordance with the results of carefully made gaugings in similar channels, to suit the conditions of the particular case in hand.

The author's conclusion that piezometric gauges can be depended upon as certainly as other appliances of precision is gratifying to note because of the facilities they offer for making gaugings of this class.

Mr. Le Conte. L. J. Le Conte, M. Am. Soc. C. E.—The author's experiments bring out clearly the well known diminution in capacity of a pipe line by reason of interior tuberculation due to 15 to 20 years' service in soft water, the reduction in the velocity coefficient in this case being 30% in 16 years. This seems to accord fairly well with the old standard formulas for the difference between the coefficients for clean and rusty pipes, which are in the ratio of eleven to eight respectively. The tables seem to show a double loss due to tuberculation, which is a new feature; that is to say, a loss due to tuberculation proper and that due simply to increased velocity of flow such as naturally accompanies the gradual increase in demand for water.

As the author states, the Kutter formula's coefficient of roughness is badly in need of another sub-coefficient. This is a most important fact for engineers to study, and brings out a fundamental defect in all the old standard formulas.

Nearly every pipe line becomes more or less foul by long-continued use, and a certain loss in capacity for discharge must necessarily follow. The loss due to tuberculation proper, as well as the loss due strictly to increase in velocity, both act prejudicially as regards future capacity of any pipe line, the only difference between any two cases being one of degree.

The chief water supplies at and near San Francisco are more or less impregnated with salts of lime, and may be classed as hard. Tuberculation is rare, and only where soft waters are in use. Pipes which have been in service for 10 to 25 years generally show a lime-scale on the inner surface, making it somewhat rougher than the new surface of asphalt; but no material change in the value of c has been noted as yet for the larger size pipes.

The formulas deduced by the author seem to fit his cases well, but whether they are suitable to apply to other cases remains to be seen. This has been the main trouble with the old formulas; they were reliable only within narrow limits near the experiments on which they were based. The results of the author's experiments should be applied to modifying the expression for n in Kutter's formula by introducing a new variable V, determined by Darcy's formula as a first approximation.

Mr. Hawks. A. McL. Hawks, Jun. Am. Soc. C. E.—The author shows in Plate VIII, Figs. 1 and 2, two radically different types of tuberculation in the pipes. As he does not state the relative positions of the two points, the writer wishes to ask for them. In recovering mains which have been replaced by larger ones he has noticed that those pipes laid in the lowest depressions were usually most affected by tubercles, and is desirous of learning if the same was true in this case.

In Plate VIII, in the immediate foreground, is shown an almost complete circle of tubercles. Is this a joint of the pipe encrusted in this

manner? The writer has also noticed that the most vulnerable places in the coating of recovered pipes seemed to be at the joints. This is probably due to the sharp edges of both the hub and spigot on the inside of the pipe being liable to be nicked in handling, and the coating on these sharp edges is very easily bruised or worn off. The slightest spot in the coating is sufficient to produce a large tubercle in a few years. In some pipes the effect of tuberculation at the joints was to diminish the clear diameter from ¼ to ½ in., not a matter of much moment to a 48-in. pipe, but a serious thing for a small service or lateral. To such an extent has this been found true, that the writer has drawn plans for joints with curves of ¼-in. radius to replace the sharp edges mentioned, and has advised, to insure perfect coating of the pipes at the joints, that the space easily reached from the end, about 3 ins. in small pipes, be retouched just before laying, with some of the asphalt varnishes which are rapid driers. Mr. Hawks.

The author does not state if he measured the area or height of the largest of these tubercles. This would be useful as showing to what extent the clear opening of the pipe might be reduced in 20 years, for conditions might easily arise whereby a ring of the largest tubercles would be formed outside of the easily protected end joints, and thereby the flow reduced, not only by the additional friction head, but by an actual reduction of cross-section. The shape of the tubercles illustrated differs materially from those observed by the writer. In the author's plates they look like barnacles with serrated tops. In pipes which have been in use from three to ten years they are smooth, rounded humps, much resembling a blister in the coating, and in that stage are very thin and easily ruptured and removed. The writer has contemplated the use of a rattler such as is used for cleaning pipes in the oil regions, for the removal of green tubercles, if the term may be used, and desires the author's opinion as to whether such means would be effective with such growths as he removed. In most cases the conduits leading to smaller cities and towns are less than 24 ins. in diameter inside, which is about the limiting size in which any successful manual labor can be performed, and with such pipes the author's methods of cleaning are not applicable.

Edmund B. Weston, M. Am. Soc. C. E.—The writer has been greatly interested in reading the paper on account of the valuable data which it contains, and the corroboration by some of these data of ideas that he expressed a number of years ago in a paper* entitled, "The Results of Investigations Relative to Formulas for the Flow of Water in Pipes." In this paper the writer states that he has come to the conclusion that two formulas constructed by an eminent French civil engineer, the late Henry Darcy, were very well adapted for pipes having interior sides similar to new cast-iron pipes. One of Mr. Weston.

* See *Transactions*, Vol. xxii, p. 1.

Mr. Weston. these formulas the writer considered applicable in cases when the velocity of flow was less than 0.33 ft. per second, and the other, which is ordinarily known as Darcy's formula, the writer was of the opinion was a safe general formula for cases when the velocity of flow is greater than 0.33 ft. per second.

For certain reasons mentioned in the paper referred to, the writer adopted the coefficient of friction, ζ, in the following formula as a basis of comparison:

$$h = \zeta \frac{l}{d} \frac{v^2}{2g}$$

In which h = the loss of head due to friction, in feet.

l = the length of the pipe, in feet.

d = the internal diameter of the pipe, in feet.

v = the velocity per second of the water flowing in the pipe, in feet.

ζ = the coefficient of friction of the water flowing against the interior sides of the pipe, $= \frac{2gh}{v^2} \frac{d}{l}$

$2g = 64.326.$

The writer, therefore, in the discussion of the present paper will use as a basis of comparison the coefficient of friction ζ. The author states that for the tuberculated pipes, the formula $v = 108 \sqrt{I}$ fits the experiments fairly well for all heads. The coefficient ζ computed from this formula is 0.0221, and the coefficient ζ computed from Darcy's formula for a pipe 48 ins. in diameter is

$\zeta = 0.0198920 + \frac{0.00166573}{d} = 0.02031.$ The coefficient ζ computed from experimental data relative to a coal-tar coated cast-iron pipe that had been in service eight years, obtained in Scotland a number of years ago by Mr. James M. Gale, and given in the writer's paper*, is 0.0204.

The writer formed his conclusions relative to Darcy's formula by comparing it with the results of 46 experiments made by 13 different experimenters in the United States, England, Scotland, France and Germany. In making the experiments 25 different pipes were used, ranging from about 3 to 90 ins. in diameter, which were new pipe, or had been in service from two to thirteen years. Some of these pipes were coated with coal-tar and others were not.

The writer's advocacy of Darcy's formula has principally been for the purpose of determining the size of pipes in the first place, and it might seem illogical, without an explanation, that he should have

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* See *Transactions*, Vol. xxii, p. 22.

Mr. Weston.

drawn his conclusions from comparisons of results derived from experiments made with pipes which had been in service as great a length of time as thirteen years. The number of experiments that had been made with entirely new pipe, however, was too limited to make use of them alone, and the writer considered that not only was it essential to provide a pipe which would furnish the required supply immediately after it was laid, but that the future capacity of the pipe, to a certain extent, should also be taken into consideration. The advisability of doing this is set forth by the author's experiments, and those made by

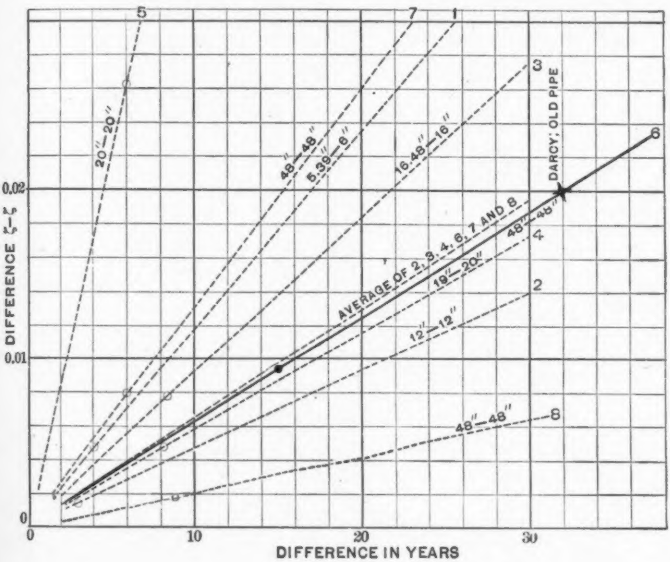

Fig. 24.

F. P. Stearns, M. Am. Soc. C. E.*, about two years after the same pipes were first laid, namely, the mean coefficient ζ computed from Mr. Stearns' experiments is 0.0126, the mean coefficient ζ computed from the author's experiments after the pipes were cleaned being 0.0128; and the mean coefficient ζ computed from his experiments immediately before the pipes were cleaned is 0.0221, showing an increase in the coefficient ζ of 0.0095 (0.0221 — 0.0126), or 75%, in fifteen years.

The increase in the coefficient ζ, which the writer has just mentioned, is shown by line No. 6, in Fig. 24.

* See *Transactions*, Vol. xiv, p. 1.

Mr. Weston. TABLE SHOWING THE INCREASE OF $\zeta - \zeta$ DUE TO YEARS OF SERVICE.

Diagram. Number.	Diameter. Inches.	Years of service.	Coefficient of friction. ζ	Average. ζ	Difference. $\zeta - \zeta$	Average rate of increase of $\zeta - \zeta$ per 10 years.	Velocity. Feet per second.	Name of Experimenter and Kind of Pipe.
	5.39	.....	.0220	......	......	....	2 50	Darcy.—New cast-iron pipe
			.0208	.....	......	....	4.19	
			.0204	......	......	....	5.62	
		New.	.0203	.0207	......	....	6.88	
	6.00	......	.0264	......	......	....	4.70	Weston.—Cast-iron pipe coated by Smith's process.
			.0249	......	......	....	7.25	
1...	......	4	.0249	.0254	.0047	.0118	8.49	
	12.00	.....	.0276	......	......	....	2.91	Simpson.—Cast-iron pipe.
			.0243	......	......	....	2.91	
			.0259	......	.....	....	4.35	
		7	.0246	.0256	......	....	4.35	
	12.00	......	.0263	......	......	....	3.57	Simpson.—Cast-iron pipe.
2...	......	4	.0277	.0270	.0014	.0047	4.11	
	16.48	......	.0197	......	......	....	2.48	Lampe.—New cast-iron pipe, coated with varnish.
			.0196	......	......	....	2.71	
		New.	.0180	.0191	......	....	3.09	
	16.00	......	.0277	......	......	....	5.25	Edinburgh Water Company.—Cast iron pipe.
3...	......	8.5	.0261	.0269	.0078	.0092	6.82	
	19.00	......	.0257	......	......	....	2.06	Simpson.—Cast-iron pipe.
			.0244	......	......	....	2.26	
			.0242	......	......	....	2.52	
			.0248	......	......	....	2.73	
		13	.0251	.0248	......	....	2.80	
	20.00	......	.0197	......	......	....	2.00	Brush.—Cast-iron pipe, coated with tar.
			.0188	......	......	....	2.24	
			.0198	......	......	....	2 36	
			.0200	......	......	....	2.52	
			.0199	......	......	....	2.68	
			.0210	......	......	....	2.76	
			.0206	......	......	....	2.92	
4...	......	5	.0214	.0202	.0046	.0058	3.00	
	20.00	.....	.0568	......	.....	....	2.71	Darrach.—Cast iron pipe, coated with tar.
			.0539	......	......	....	3.01	
			.0508	......	......	....	3.31	
			.0482	......	......	....	3.61	
			.0459	......	......	....	3.91	
			.0437	......	......	....	4.21	
			.0413	......	......	....	4.51	
			.0394	......	......	....	4.81	
5...	.....	11	.0376	.0464*	.0262	.0437	5.11	
	48.00	......	.0120	......	......	....	2.62	Stearns.—Cast-iron pipe, coated with coal-tar.
			0131	......	......	....	3.74	
			.0128	......	......	....	4.97	
		2	.0124	.0126	......	....	6.20	
6...	48.00	17	....	.0221	.0095	.0063	....	FitzGerald.—The same.
7...	48.00	8	.0204	.0204	.0078†	.0130	3.46	Gale.—Cast-iron pipe, coated with coal-tar.
8...	......	......	....	.0204	.0017‡	.0019		

* Between data of Brush and Darrach.
† Between data of Stearns and Gale.
‡ Between data of FitzGerald and Gale.

In the above table, in addition to those mentioned, are given differences between coefficients ζ that have been computed from the

results of experiments made with pipes that had been in service different lengths of time in the United States, England, France and Germany. These differences are simply presented as a very slight verification of the law of increase shown by the experiments of Messrs. FitzGerald and Stearns, as the coefficients ζ for each diameter of pipe were worked out from experiments made at only one period with each pipe, the experiments not being repeated after the pipes had been in service a longer length of time; consequently, the differences are those of coefficients ζ computed from experiments made with different pipes, whereas those of Messrs. FitzGerald and Stearns were made with the same pipe. These differences are also plotted in Fig. 24 and have been grouped in order to show the increase in the coefficients ζ due to years of service, as follows: 5.39 and 6 ins.; 12 and 12 ins.; 16.48 and 16 ins.; 19 and 20 ins.; 20 and 20 ins.; 48 and 48 ins.; and 48 and 48 ins. The average of the six lines numbered 2, 3, 4, 6, 7 and 8, which the writer thinks are the most reliable, is also plotted in Fig. 24. Mr. Weston.

The coefficient ζ computed from Darcy's formula for old pipes is just double the coefficient ζ computed from Darcy's formula for new pipes (for a pipe 48 ins. in diameter, $2 \times 0.02031 = 0.04062$), and it is shown by plotting the difference between the coefficients ζ for old and new pipes ($0.04062 - 0.02031 = 0.02031$), upon line No. 6 of Fig. 24, that the increase 0.02031 corresponds to a length of time of about 32 years.

By the aid of these data the writer suggests a new method of applying Darcy's formula by which the number of years that a pipe has been in service can be taken into consideration, namely, the coefficient ζ for new pipes being, as before mentioned, $0.019892 + \frac{0.00166573}{d}$, a new variable coefficient ζ_1 for any number of years of service may be approximately determined thus, $\zeta_1 = \left[\zeta + \left(\zeta \ \frac{1}{32} \ y\right)\right] = [\zeta + (\zeta \ 0.0313y)]$, y being the number of years of service.

The following table gives the discharge of a 48-in. pipe, having an inclination of 0.002, after it has been in service a specified number of years. The table was computed by using the variable coefficient ζ_1 in the formula $v = \sqrt{2\,g\,h} \div \sqrt{\zeta_1 \frac{l}{d}}$

Number of years in service.	ζ_1*	Discharge in gallons per 24 hours.
New.	0.02031	40 879 000
5	0.02349	38 012 000
10	0.02667	35 673 000
20	0.03302	32 060 000
50	0.05210	25 523 000
100	0.08388	20 115 000

* With the exception of $0.02031 = \zeta$.

Mr. Weston. The results given in the table appear reasonable. As can be seen by the table, the capacity of the pipe, owing to tuberculation, is reduced 38% after 50 years' service; and after 100 years' service 51%. or to the capacity of a new pipe about 36 ins. in diameter. A pipe 6 ins. in diameter under the same conditions would discharge when new 211 000 galls. per 24 hours, and after 100 years of service 104 000 galls. per 24 hours, or a reduction in capacity of 51% (as given above for the 48-in. pipe), which would be equivalent to the discharge of a new pipe about 4.5 ins. in diameter.

One of the best experimental illustrations of the reduction of the diameter of a pipe owing to tuberculation that the writer is familiar with is as follows:

The diameter of the pipe was determined with great accuracy before and after being cleaned, by filling the pipe with water and carefully measuring the same by means of a special apparatus arranged for the purpose. The average diameter of the pipe before the interior deposit was removed was 9.575 ins., and the average coefficient ζ was 0.0473. After the pipe was cleaned the average diameter was 9.634 ins., and the average coefficient ζ, 0.0271. The discharge of the pipe, at an inclination of 0.002, before it was cleaned, considering the above figures, would be 482 450 galls. per 24 hours, and after it was cleaned, 637 380 galls. per 24 hours.

A summary of these results shows that the coefficient ζ was increased by tuberculation 75%, the capacity of the pipe reduced 24.3%, and the diameter reduced 0.6%. Using the coefficient $\zeta = 0.0271$ of the cleaned pipe, in the formula before mentioned for determining the velocity, the inclination being the same, a clean pipe about 8.61 ins. in diameter would have the same capacity as the pipe 9.575 ins. in diameter before it was cleaned.

It may seem as though the writer was somewhat inconsistent in his suggestions relative to the variable coefficient ζ_1 as he has assumed as a coefficient ζ for new pipe one which was verified by experimental data of pipes of an age ranging from that of new pipes to those which had been in service from about two to thirteen years; and it might be thought that if the coefficient ζ_1 was increased owing to years of service, that the coefficient ζ used as a base should be assumed to be that of a pipe that had been in service a specified length of time, and therefore decrease in value for this specified length of time until the age of absolutely new pipe was reached.

If criticisms similar in purport to the above should be advanced, the writer's reply would be that Darcy's formula for new pipes had been proved to be a safe and reliable formula, and that experimental data obtained with a single diameter of pipe were not of sufficient magnitude for determining a correction to be applied to a formula which is intended to be used for pipes of all diameters. Also, that the variable

coefficient ζ_1 which takes into consideration the number of years that a pipe has been in service, is simply suggested as a reasonable approximation which has been based upon the only reliable data known to the writer, that have been derived from experiments made with the same pipes, when new and old, at an interval of time between the experiments which is positively known. It would hardly be possible to construct a reliable formula in which the length of service of a pipe was considered which could be generally used, as several important elements would enter into the case. For instance, the corrosion of the interior of an iron pipe is proportional to the volume of water flowing in it—the greater the volume, the more the corrosion; and the chemical constituents of the water exert an influence one way or the other, slightly alkaline and aerated waters causing cast-iron pipe to corrode much more quickly than some other waters differently constituted. Mr. Weston.

In closing, the writer would remark that in making use of a formula known to be safe for determining the size of supply or distribution pipe, the only criticism that an engineer is likely to receive is that his estimates of cost are too high. A criticism of this kind, however, generally helps the reputation of an engineer, as it is apt to give the impression that he is a safe man. The engineer, however, who tries to figure out the size of a pipe to the lowest possible limit on account of first cost, if the pipe does not come up to the capacity for which it was intended, is very likely to be blamed for having made a mistake, and his well-meant intentions in regard to first cost are, in the majority of cases, more likely to be ridiculed than praised.

George W. Rafter, M. Am. Soc. C. E.—The paper is of interest to the writer by reason of the well sustained conclusion that piezometer measurements accurately indicate the loss of head in a pipe line working under pressure, as well as for the light thrown upon the influence of the interior surface of pipes on the discharge. The vast importance of a protective coating that shall absolutely protect is forcibly presented. A number of years ago the writer studied the practice of American pipe foundries as regards the ordinary protective coating devised by Dr. R. Angus Smith, and came to the conclusion that at some of the foundries, at any rate, the coating was applied so carelessly that failure was fairly certain. As illustrating this point it may be mentioned that there are now cast-iron mains, laid in 1873, in the streets of Rochester, N. Y., in which the coating was about as perfect in 1890 and as free from blemish as when first laid; while pipe from other foundries laid several years later showed in 1890 very much the same appearance of the interior surfaces that is indicated in the illustrations in the paper. With the present knowledge the difference in such a case must be ascribed almost entirely to differences in quality of the material of the coating, or to defects of some sort in the method of applying it. Mr. Rafter.

Mr. Rafter. In the course of the study of coatings referred to, letters were addressed to several of the leading foundries asking for a detailed account of the formula in use at each foundry. The interesting point revealed was that in many cases the entire business of coating was a purely routine matter, which, from the foundryman's point of view, at any rate, was of relatively little importance. At one foundry at which the writer had occasion to spend considerable time there was no person with any knowledge whatever of the composition of the coating. A proprietary preparation purchased in large quantities was used without test and without question from anybody. So long as the coating hardened readily and adhered, it seemed to be assumed that every necessary condition had been fulfilled. The fact that the material used for producing the coating was a complex one, and hence necessarily subject to special conditions for the best results, was entirely overlooked.

Facts of the character of the foregoing lead easily to the conclusion that as regards the coating of water mains much information is needed. If the Boston water has a specially destructive effect on the coating, that fact should be strongly brought out by technical investigations, and, when established, a special coating devised for Boston mains to meet the emergency. In the same way the effect of other waters upon the ordinary coatings should be studied, and, if necessary, different preparations devised to meet the various cases. On this point it may be remarked that it seems very probable that the Boston waters are specially destructive in their action and some of the earlier information of the Boston Water-Works reports is interesting and valuable on this point.* The softness of the waters about Boston may be assigned as the chief reason for the specially destructive action.

The process of coating as ordinarily applied to cast-iron pipe was devised by Dr. R. Angus Smith, and first used on the mains of the Manchester, England, Water-Works about 1849 or 1850. Inasmuch as information about this very common operation is not easily obtained, the writer refers to it here.

According to Mr. Bateman† the process as originally used at Manchester consisted of immersing the pipes when hot in a bath or cauldron of boiling coal pitch after the naphtha compounds were distilled off. The residuum was then hard, insoluble, odorless and tasteless, and required an admixture of mineral oil to enable it to acquire, when boiled, proper fluidity for the operation.

The experience at Manchester demonstrated that if rusting, however slight, had taken place on the surface of the pipe, the coal pitch coating peeled off. The proving of the Manchester pipes was all done

*See "Annual Report of the Cochituate Water Board for 1852"; also "A History of the Introduction of Pure Water into the City of Boston," Boston, 1868, pp. 149 to 166.

† History and Description of the Manchester Water-Works. By J. F. La Trobe Bateman London and Manchester, 1884, pp. 143–146.

by the corporation before the application of the protective coating, and in order to prevent rusting the pipe foundries were required to paint the pipe with linseed oil, both inside and outside, as soon as the sand was cleaned off and while the pipe was yet warm. In this condition the pipe was delivered to the corporation for proving and coating. The proving consisted in subjecting them to a hydraulic pressure equal to 300 ft. head, after which they were heated in a vertical pan and then immersed in another containing the boiling coating, into which they were slowly lowered, still in a vertical position, and raised again. The heating drove off any slight rust or dampness and allowed the coating to penetrate the pores of the iron, which were slightly opened thereby. Mr. Rafter.

Mr. Bateman states that the resulting smooth surface added materially to the volume of water discharged. When the coating was fresh the increase over the quantity indicated by the ordinary formula was 40 to 50 per cent. He also states that an examination of some of the 36-in. pipes which were coated in this manner and had been laid 30 years at the date of examinations, showed that no corrosion had taken place inside, but that they were still as clean as when first laid. While at Manchester in October, 1894, the writer took occasion to inquire as to the present condition of the pipe first coated by Dr. Smith's process, and was informed that so far as the Water Department had information, derived from cut-outs, etc., they were still generally as clean as when first laid.

Mr. Bateman said further that where the oiling was neglected and the quality of the coal pitch not what it should be, the pipes had frequently to be discarded. He had, therefore, always insisted on the oiling previous to the coating. He also said that waters of more than 4 or 5 degrees of hardness precipitate an incrustation of lime on the interior of coated pipe the same as uncoated, which will in either case eventually choke the pipe.

The first use of pipe coated by Dr. Smith's process in the United States was pipe imported from Glasgow for the Brooklyn Water-Works in 1858.* The Brooklyn specification has been the basis of most of the pipe-coating specifications thus far used for cast-iron pipe in the United States. These specifications begin by stating that the conditions laid down must be strictly observed in order to insure the permanence of the coating and the efficient protection of the pipe from rusting. Some pipe foundries are not following this original specification closely which, so far as known, has not been improved thus far.

The original cast-iron mains of the Rochester Water-Works were coated under the original Brooklyn specification properly followed, and

* See "The Brooklyn Water-Works and Sewers, a Descriptive Memoir." New York, 1867, p. 41.

Mr. Rafter. it is believed from the examinations made by the writer five years ago that this coating is generally intact to this day. The wrought-iron conduit of the Rochester Water-Works was, however, coated by a quite different formula, derived, it is believed, from Californian experience. The following is the specification for this coating:

" *First.*—Every pipe must be clean and free from earth, sand, or rust, when the coating is applied, and no pipe shall be coated until the authorized inspector shall have carefully examined it in reference to compliance with the above requirement.

" *Second.*—The coating mixture shall be prepared and applied to the satisfaction of the chief engineer and in the following manner: The purest quality of asphaltum, such as shall be approved by the chief engineer, shall be procured and broken into pieces containing from two (2) to four (4) cu. ins. and placed in kettles over a heating furnace; then the interstices between the pieces are filled with the best quality of coal tar, free from oily substances, and the whole boiled and stirred up in such manner as the chief engineer may direct from three (3) to four (4) hours until the kettle charge is a semi-fluid mass. During the boiling such occasional tests shall be made as may be required by the chief engineer to determine the quality and character of the mixture and test its adaptability for the purpose intended.

" When the mixture is in proper condition it shall be drawn from the kettles into a reservoir over a heating furnace or oven of sufficient capacity to enable the pipes in lengths up to thirty (30) ft. to be thoroughly dipped.

" Immediately after being taken out of the coating bath, a piece of the coated iron is to be plunged into water near the freezing point, and if after removal the coating does not become brittle with a tendency to fly off or loosen when pipe is rapped with a hammer, but firmly adheres to the iron, the material will be considered of good quality, and the work properly done in ordinary cases, although the engineer may subject the same to such other tests as he may deem desirable.

" After the shorter pieces of pipe are riveted or bolted together and placed in a trench, a workman shall be sent through the pipe with a small kettle of the mixture and thoroughly coat the newly riveted joints, rivets and laps, and all other places where the coating has been marred, injured or destroyed in any manner. The same shall also be done on the outside of the said pipe, either before or after the laying in the trench or both, if required."

Recapitulating the subject of pipe coating it may be remarked:

First.—Mr. Bateman observed over 40 years ago that a smooth interior coating increased the delivery of a pipe when the coating was new from 40 to 50% more than indicated by the formula then in common use.

Second.—The maintenance of the integrity of the coating is a matter of supreme importance, and hair-splitting formulas are of absolutely no use so long as an indefinite reduction of the delivery is possible, due to a more or less constant deterioration of the interior coating.

Third.—As regards cast-iron water mains the coal pitch preparation of Dr. R. Angus Smith as originally applied at Manchester is the best thus far devised. So far as is definitely known it protects the pipe in-

definitely if applied strictly in accordance with the original specification. Mr. Rafter.

Fourth.—In view of the present knowledge of the matter, serious tuberculation of a pipe coated by Dr. Smith's formula within 25 or 30 years is probably presumptive evidence of improper or careless application of the coating. In drawing the fourth conclusion it is recognized, however, that coal pitch is a substance more or less subject to change, and there may be some waters which accelerate these changes more than others. On this general subject more information is needed.

Fifth.—This conclusion is stated in the form of a question. Is there any good reason why a coating should be used for wrought iron or steel pipe different from that used for cast iron?

In the writer's paper* on the "Hydraulics of the Hemlock Lake Conduit of the Rochester, N. Y., Water-Works," there is expressed a mild doubt as to the correctness of the value of c in the expression $v = c\sqrt{r\,s}$ as applied to pipes of long lengths and large diameters. Since the presentation of that paper in 1892, the views of hydraulic engineers have undergone some considerable clarification through the operation of forces to which it is unnecessary to refer specially. As regards coated cast-iron pipes of great length and large diameters the doubt is effectually removed so long as the integrity of the interior coating is effectually maintained. On the other hand, for built-up wrought-iron or steel lapped and riveted pipes the doubt has equally resolved itself into a certainty. It is known definitely that for such pipes large values of c in the Chezy formula are entirely inapplicable. Even when the pipes are new, the irregularity of the interior surfaces, caused by the projecting rivet heads as well as the lap of the sheets, introduces disturbing elements fatal to high efficiency.

In concluding the discussion of his paper on the "Hydraulics of the Hemlock Lake Conduit" the writer expressed the view that, as a matter of rational design, the built-up pipes are only applicable when by reason of high pressure or large diameter cast iron cannot be used safely. This view is strengthened by later developments. Certainly the assumed economy of the built-up pipes is considerably decreased by the necessary increase in diameter in order to compensate for the disturbing action of the rivets and the lap.

There is, moreover, one further consideration in favor of cast-iron pipes, namely, that cast iron is a material much less easily corroded than either wrought iron or steel, and hence, *per se*, a less difficult material to shield properly by the protective coating. It seems clear that a failure to appreciate this point has been the source of ultimate unnecessary expense to some of our municipalities where the built-up conduits have been used, and where they have been adopted on only a slight margin of first cost in their favor, and, so far as known, without regard to the final results.

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* See *Transactions*, Vol. xxvi, p. 13.

Mr. Herschel. CLEMENS HERSCHEL, M. Am. Soc. C. E.—If a meter were put into each of the 48-in. pipes described in the paper the record of the meters would show the gradual diminution of, possibly an occasional or regular or annual fluctuation in, the discharge of the two pipes.* As an effective meter for 48-in. pipes and for pipes of any diameter was described in the *Transactions*† in 1888, and has since become an established method of metering water, the opportunity was here presented of using such a meter, instead of the more costly, cumbersome and merely transient method of weir measurements. Indeed, it would not be surprising if the present set of experiments proved to be the last set of weir experiments ever made for the like purpose. In the progress of the arts there has to be a last time for all kinds of ways and methods; and in the nature of things there will have to be a last time when weir measurements are to be undertaken to meter the flow through a couple of 48-in. pipes forming part of a system of water supply.

In the *Journal* ‡ of the New England Water-Works Association is an account of the test of a 48-in. Venturi meter, and its results are compared with those found in 1886 in the test of a 12-in. and a 108-in. meter of the same sort. These three tests show a conformity with each other not found in weir experiments. The theory of the Venturi meter also is simplicity itself compared with that of a discharge over a weir,§ and, beside this, various users of the meter have tested it for themselves, so that, to him who will enquire or study, the accuracy of a Venturi meter will speedily stand established. It is less likely to err than a weir, because it acts in conformity to simple instead of according to complex hydraulic laws, and both use and experiment show it to be exceedingly uniform in its results.

It costs much less than a weir in first cost, and still less to operate. The writer has endeavored to secure from the author of the paper the recorded cost of the apparatus described, and of the experiments conducted with it. In default of receiving this statement, the following estimate of an experienced foreman and millwright is given:

* To illustrate. On March 2d, 1896, the State of New Jersey was visited by a cold, violent northwest wind, following a freshet that had removed the ice from rivers and ponds. This wind and cold lasted without interruption for more than 72 hours. The consequence was that the water-works of Camden, Trenton, the East Jersey Water Company, Paterson, Newark and Jersey City were all either shut off entirely or sadly diminished in carrying capacity by anchor ice. The 48-in. riveted steel conduit of the East Jersey Water Company, which has such a meter on it, had been carrying 36 000 000 galls. per 24 hours. During the period of anchor ice it carried about 23 000 000 galls. per 24 hours. After the scouring it got from ice that entered the gate-house through broken screens, and past screens lifted out of the way to keep the water running, it was found to carry 37 500 000 galls. This immediately suggests, as a safe and effective way of cleaning water pipe, to give them annual doses of cracked ice in liberal quantity.

† Volume xvii, p 228.

‡ Vol. viii, p. 35.

§ See on this point Merriman's "Treatise on Hydraulics," Art. 71.

Mr. Herschel.

Carpenter work at siphon chamber, Figs. 8 and 9	$444
Lumber	156
Iron work	225
Brass pipes	50
Piezometer sleeves	500
Piping	150
Gauges and shelters	300
	$1 825
Weirs and gauges at terminal chamber	600
	$2 425

The time spent in taking observations and making computations must have been not less than five months of three gate-tenders and four observers and computers.

For a moderate estimate:

Three men at $60 per month	$900
Four " $75 "	1 500
Total expenditure for experiments	$4 825

Instead of this, a wooden Venturi meter with brass-lined cast-iron throat piece could have been built inside of the two 48-in. pipes, precisely like the meter described in the *Journal* of the New England Water-Works Association, and each one furnished with a register for less than half the money. The meters would have had the enormous advantage of continuing their record indefinitely, as long as the pipe lasted, and at a mere nominal expense of operation, instead of having to be pulled out, as had to be done with the weirs, and instead of requiring a large outlay for operation while the weirs remained.

The presence of a weir greatly disturbs the hydraulic gradient, as it necessitates the formation of a pond of still water up stream from the weir, and a depth of water flowing over the weir, on top of this pond, in addition; about 4½ ft. vertical fall in Fig. 17; whereas, a 4-ft. Venturi meter, made to meter the same range of velocities (0.5 to 7.25 ft. per second), and to keep the loss of head at a small amount, would have been made with a throat area of about two-ninths the full area of the pipe, and would, at 7.25 ft. velocity, have shown a loss of head in passing the meter of about 2.2 ft. The velocities of 5.5 and 3.6 ft. mentioned would have shown a loss of head of about 1 and 0.4 ft., respectively.

The difference between $c = 110$ and $c = 140$, or between the clean pipe and the pipe after 18 years' use, means a loss of head on 1 800 ft. length, due to tuberculation alone, when $v = 7.25$, 5.5 and 3.6 ft. per second, of 3, 1.7 and 0.7 ft. respectively, or of more than would be caused by a Venturi meter.

Mr. Herschel. On page 258 are given some "formulas chosen for the present investigation," but if the paper teaches anything it shows that the chart of logarithmic homologues had not been finished, and its derivative exponents had not been determined before the pipes experimented on had changed their carrying capacity sufficiently to render these exponents inapplicable. Looking back over the hydraulic literature of the past 30 or 35 years, it seems to the writer that he could readily count up at least twenty different sets of formulas set up during that time, each one as the best with which to compute the carrying capacity of pipe lines. Nearly each year sees such created, each one derived, first, from a penible fitting and swinging of plotted curves to represent as well as they may certain plotted experiments; and second, by means of one of the several mathematical sleights of hand devised to convert curves into formulas. All such formulas are delusive, because they portray only the discharge of the pipe or pipes in question at one certain period of their life; whereas, it is more important now to get the discharge of the same pipe, and of many kinds of pipe, at many periods of their life. The paper is perhaps unique in literature on the subject, as giving the discharge of the same pipe at an interval of many years, and nearly so as giving such discharge before and after cleaning.

It is true that to get the law of variation due to the different sizes and slopes of the same kind of pipes, it is necessary to compare them when they are new or smooth, but this seems to have been sufficiently attended to. Where a coefficient for the same pipe varies in 18 years from 110 to 140, the form of the formula becomes of minor importance, and the Chezy form will be considered by most engineers as good enough for all practical purposes, the coefficients being once closely determined. Possibly the use of the Kutter scale of roughness, or of improvements upon that scale, may eventually make it easier to find the coefficient by judgment alone, though the writings of engineers do not yet indicate that a scale of roughness is a materially better aid to finding true coefficients by judgment alone than a table of the coefficients themselves.

It is easy to adduce examples. Thus, Rudolph Hering, M. Am. Soc. C. E., in discussing the paper by George W. Rafter, M. Am. Soc. C. E., on the "Hydraulics of the Hemlock Lake Conduit," * takes Kutter's coefficient n, for 36-in. and 24-in. new riveted pipe as 0.011, while he takes it as 0.012 for new cast-iron pipe; when any tyro in 1896 can compute for himself that it should have been taken at least equal to 0.013 for new riveted pipe; and when every beginner also knows now that it is equal to 0.016 under some conditions of use for that kind of pipe. For a 4-ft. pipe laid on a slope of 2 in 1 000, the difference between $n = 0.011$ and $n = 0.012$ is the difference in the co-

* See *Transactions*, Vol. xxvi, p. 40.

efficient between 145 and 130, or a difference of 11.5% in the discharge; and the difference between $n = 0.011$ and $n = 0.016$ is the difference in the coefficient between 145 and 95, or a difference of more than 34% in the discharge. Mr. Herschel.

Mr. Hering had, in 1888, translated and extended Kutter's book, and was therefore presumably as well posted in 1892 on the use of the Kutter formula as anybody. He had Mr. Rafter's carefully written paper before him, which gave for the first time reliable gaugings of the Rochester conduit, but in spite of all that, the use of the Kutter coefficient could not prevent him from making what would have to be counted as an error due to negligence, except for the facts noted, that even in 1892 the construction and computation of the carrying capacity of large riveted conduits was yet a new thing. Engineers then or up to that time most conversant with long conduits of that kind, had united in opinion and in publications on the subject in treating it as of a similar degree of interior roughness as cast-iron pipe, and also as not subject to material deterioration of interior surface in the course of time like cast iron. So the record shows, that in spite of the use of the Kutter coefficient of roughness, an able engineer like Mr. Hering was, in 1892, legitimately under the same or a similar delusion with regard to the proper coefficient to apply in computing the carrying capacity of riveted pipe and with regard to the true carrying capacity of the Rochester conduit, as the record shows a long line of eminent and able engineers, also the writer, to have been, up to 1889 or 1890. Over and above all this, those who have themselves experimented on riveted conduits know that Kutter's coefficient of roughness does not compute a constant for one and the same pipe, during one and the same series of experiments. It varies sufficiently to cause the discharge to vary 25 or 30% from what it would be on the assumption of either of the two extremes of degree of roughness applicable to the same pipe at any one time, this roughness varying with the velocity. This is especially true in cases of a high range of velocities, and it is not yet properly determined when the coefficient c increases and when it decreases with the velocity.

Another such case is pointed out on page 257 of the paper now under discussion, by showing that the Kutter coefficient of roughness for tuberculated pipe varied with the velocity from 0.012 to 0.014, meaning a possible variation of discharge as 110 to 130, or 18%, according as the pipe be assumed to belong to one category of roughness or the other.

Another such case is found on page 141 of Mr. Hering's translation of Ganguillet and Kutter's "Flow of Water in Rivers and Other Channels," where the Kutter coefficient of roughness varies with the velocity from 0.0127 to 0.0160, meaning a possible variation of discharge

Mr. Herschel. as 112 to 142, or 27%, according as the pipe be assumed to have one degree of roughness or another.*

These cases should be sufficient to show the lack of support to be derived from a Kutter coefficient of roughness, in computing the discharge of a new kind of water channel. They should prove that a claim of increased accuracy to be derived uniformly from its use is in error, for a coefficient of roughness which represents the roughness of a pipe as changeable within a minute or a second to an extent of affecting the discharge 25% and over is a misuse of terms, and is itself no better than the plain coefficient it endeavors to replace. It is worse, because one variable coefficient is better than two. In other words, Kutter's coefficient, in many cases, does not apply, and for such is worthless. It was worthless for riveted pipe in 1889, and is yet, possibly, because Kutter had not had sufficient experiments on this kind of pipe at hand to use in constructing his empirical formula. It is better as an aid to an exhibition of afterthought, than it is to facilitate the exercise of prevision or of prophecy, unless used for old and tried cases, and such as were used in setting up the empirical formula.

The writer is at this time in position to make experiments on many kinds and sizes of riveted conduits. He is making such, as occasion demands, and has long intended to find their coefficients and to publish them in digested form, when somewhat complete. At present, the data available concerning this kind of conduit, so far as the writer has yet seen them published, are still too meager to permit of aught but ill-founded, possibly illusive, and mere ephemeral speculation and discussion.

Referring again to the exponential formulas of the paper, there is, in the writer's opinion, no utility, in the present state of the knowledge on this branch of hydraulics, in setting up specific formulas to represent specific experiments or gaugings. As a diversion from the line of advance on which such studies should be concentrated, there may even be in it somewhat of impropriety.

Toward the close of the paper is this sentence: "The author is particular in calling attention to this fact, on account of slurs that have been cast by some hydraulicians upon piezometric observations." It will take additional observations to those recorded in the paper to instruct an expectant profession on the value and the true meaning of this class of record readings. It has been observed, for instance, that piezometers do not always read alike, when tapped into a pipe at different points in the circumference of a pipe. This is noted on page 248, Vol. XVII of *Transactions*, and is also discussed in Merriman's "Treatise on Hydraulics," Articles 70 and 84.

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* The gauging here referred to is erroneously stated to have been made with a Venturi meter. It was made over weirs, of the water flowing in a tube subsequently fitted with a Venturi meter.

The opportunity existed during these experiments to renew the inquiry into this phenomenon, to note which it would only have been necessary to tap more than four piezometers into the pipe at the several stations, and to take observations on each tube separately. But by tapping four only and then connecting the lead pipes in pairs, the phenomenon, if it existed in this case, must have been obscured beyond recognition. Mr. Herschel.

The piezometers described in the paper were 1 in. in diameter, which is an unusually large size. The writer introduced the method of leading the orifices from the pipe into a pressure chamber, and then attaching the gauge tube to the pressure chamber, and this method has given good results in the hands of other experimenters, but should be further experimented on.

It certainly is not clear to-day, any more than it ever was, whether piezometer readings are wholly a function of the mean velocity, or partly, at least, of the surface, or some other internal velocity of the water contained in the pipe also, or how they are affected by position, angular or otherwise, or perhaps by size, or just what is the best and hydraulically most accurate and perfect way of constructing and placing them, or what should be the standard way of constructing and placing them. So that it is fair to assume, that much still remains to be sought and discovered of matters relating to piezometers.

Desmond FitzGerald, M. Am. Soc. C. E.—The only portions of the discussions which call for serious attention are those which attack the propriety of the exponential form of equation submitted by the author. Mr. Hering champions the Kutter formula warmly, as might have been expected from his long and able work in connection with its use by American engineers. Mr. FitzGerald

The value of Kutter's work is appreciated by the author, who was careful to give the results of his experiments in the Kutter as well as the exponential form. If, however, it should appear from recent gaugings that the monomial form of equation, with variable exponents, is capable of a wide and accurate application, and that it is both simpler and easier to use, the author sees no reason for clinging blindly to any other formula, no matter what its history may have been. It is known now that the Chezy formula upon which Kutter's is built is founded upon a serious error. Resistances do not vary exactly as the square of the velocity, however much the text books may insist to the contrary.

Mr. Hering believes, however, that the "only" proper course to pursue is to start with the Chezy formula. The difficulties met with will be apparent upon a close perusal of Mr. Hering's graphic description.

Mr. FitzGerald As early as 1850 M. Barré de Saint-Venant* proposed a formula with two arbitrary constants which he attempted to ascertain. From the data then existing he found the index of the velocity to which the resistances were proportional to be 1.71 instead of 2.0 in the Chezy formula. It is known now that 1.71 is a very low index and represents an extraordinary degree of smoothness in the channel, corresponding to tin plate.

Is it an "impropriety" to turn backward to the exponential form? The future must of course determine this. Its introduction in the paper was done at least after long deliberation, and before condemning it the author asks the student of hydraulics to study carefully the works of Saint-Venant, Hagen, Reynolds, Unwin and Foss. The last has shown that a number of trustworthy gaugings of cast-iron pipes give 1.88 as the exponent fitting closely the experiments on clean pipes, whatever their size or inclination.

The author found 1.91 in his experiments, and Prof. Unwin deduced 1.95 from his examinations. If it be true that a coefficient of roughness can be found which is constant for any given surface, whatever the slope, size and shape of the channel, then a valuable ally has been found whose acquaintance it is important to cultivate. It seems to the author that it must be as easy for an engineer to use a monomial formula with an exponent which can be varied to suit the varying conditions of roughness of channel as to apply the more complicated method of Kutter.

If Mr. Herschel's optimistic statements in regard to the Venturi meter are correct, then he is to be congratulated upon this remarkable revolution which has already relegated the weir to obscurity. Still the author is not persuaded that he would have done better to use the meter in these particular experiments. It would have been impossible to carry the velocities to over 7 ft. per second, as was done with the arrangement of weirs, and perhaps it might have been desirable to rate the meter by means of the weir. As far as the cost of the experiments is concerned, the author wrote Mr. Herschel that it would have been furnished to him had it been possible without much time and trouble. The work was carried on almost entirely by the regular maintenance force, and there seemed no sufficient reason to justify an investigation into the expense.

The author hopes that whatever this may have been, the results may prove of value to the profession. Mr. Gould seems to be uncertain on this point. The author is very sorry that the 48-in. pipes discharged so much more water than Mr. Gould seems to think they should have done. It is to be hoped that notwithstanding that gentleman's faith in the Darcy formula, he will not worry himself very much over fearing

* *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences*, Paris, XXXI, 1850, pp. 283-6, 581-3; *Annales des Mines*, XX, 1851 (4me Series), Vol. 61, running number.

"that dangerous generalizations may arise from these experiments." Mr. FitzGerald Heights of the water in the gate chambers were properly recorded and will be furnished Mr. Gould on application.

Mr. Herschel says:

> "If the paper teaches anything it shows that the chart of logarithmic homologues had not been finished and its derivative exponents had not been determined before the pipes experimented on had changed their carrying capacity sufficiently to render those exponents inapplicable."

This is rather a formidable way of saying that if the flow through a pipe is measured, the calculations are hardly cold before the carrying capacity of the pipe has diminished by tuberculation. The value of this remark lies in its application.

In answer to the criticism upon the piezometers, the author can only ask Mr. Herschel to study the agreement between the readings of the piezometers, whether deduced from the tube piezometers lying flat upon the bottoms of the pipes or those screwed into the sides of the pipes. It was no part of the problem to determine the effect of piezometers set at angles to the flow of the stream, which has already been done by other experimenters.

Mr. Weston defends the Darcy formula with ability. As long as that formula gives results upon the safe side no one is hurt, but is it desirable to apply a formula to the discharge of a large clean main which really gives the discharge of an old and tuberculated main? Is it not misleading and liable to obscure the important fact that the carrying capacity of a pipe decreases rapidly with the changes which take place in the nature of the wetted perimeter as the pipe ages?

The following information is in answer to questions asked by Mr. Hawks. It is true that the circle of tubercles disclosed by the photograph is at a joint. The author, however, does not think that the joints generally showed this effect. Some of the tubercles were half an inch in height, but no blistering was noticed. The author does not know how well a rattler would work in removing tubercles.

A volume might be written upon the subjects suggested by Mr. Rafter. It is true that the coal tar used in coating cast-iron pipes is very carelessly applied in some foundries. There is ample room for reform in this direction. Much more attention should be given to the lining or coating of pipes. In the case of large mains the author has frequently noticed great ridges or concentric rings in the interiors and he has some fine photographs which show this common fault. The rings are caused by the impressions made in the soft clay cores by the process of leading, where the leading is done by hand with a large brush. The general lack of smoothness in the interiors of mains and the careless coating of the pipes after they are cast are ex-

Mr. FitzGerald pensive additions to the frictional resistances and consequent losses of head.

An experiment recently made by the author on a new 36-in. main a mile in length gave $v = 136\ (R\ I)^{\frac{1}{2}}$ for a velocity of about 4.7 ft. per second. It forms part of a series of measurements on this pipe at different velocities.